ADHESIVE PENETRATION IN LAMINATED OIL PALM TRUNK VENEER

M Siti Zalifah[1], S Abdul Hamid[2], K Izran[2], A Mansur[3] & S Mohd Nazip[3]

[1]*Faculty of Applied Sciences, Universiti Teknologi MARA Pahang, 26400 Bandar Jengka, Pahang, Malaysia: ifah@pahang.uitm.edu.my*
[2]*Forest Research Institute Malaysia, 52109 Kepong, Selangor Darul Ehsan, Malaysia*
[3]*Faculty of Applied Sciences, Universiti Teknologi MARA Shah Alam, 40450 Shah Alam, Selangor Darul Ehsan, Malaysia*

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SITI ZALIFAH M, ABDUL HAMID S, IZRAN K, MANSUR A & MOHD NAZIP S. 2013. Adhesive penetration in laminated oil palm trunk veneer. This study investigated the bond formation of formaldehyde adhesives impregnated into laminated oil palm trunk (OPT) veneer. Adhesives used for the study were phenol formaldehyde (PF) and urea formaldehyde (UF). The adhesive penetration was determined through effective penetration, average penetration and maximum penetration at different hot pressing temperatures (125 and 130 °C for PF, 115 and 125 °C for UF), OPT portions (top and bottom) and OPT veneer parts (outer and inner). In general, adhesive penetrations using PF and UF adhesives were significantly different between veneer parts, hot pressing temperatures and portions. These results showed that temperature and porosity of veneer surfaces influenced adhesive penetration.

Keywords: Effective penetration, average penetration, maximum penetration, phenol formaldehyde, urea formaldehyde, OPT

SITI ZALIFAH M, ABDUL HAMID S, IZRAN K, MANSUR A & MOHD NAZIP S. 2013. Penembusan perekat dalam venir batang kelapa sawit berlaminasi. Kajian ini menyiasat pembentukan ikatan perekat formaldehid dalam venir batang kelapa sawit berlaminasi. Perekat yang digunakan dalam kajian ini ialah fenol formaldehid (PF) dan urea formaldehid (UF). Penembusan perekat ditentukan melalui penembusan berkesan, purata penembusan dan penembusan maksimum pada suhu penekanan panas yang berbeza (125 °C dan 130 °C untuk PF, 115 °C dan 125 °C untuk UF), bahagian batang kelapa sawit (atas dan bawah) dan bahagian venir (luar dan dalam). Secara umum, penembusan perekat menggunakan PF dan UF berbeza dengan signifikan antara bahagian venir, suhu penekanan panas dan bahagian batang kelapa sawit. Keputusan menunjukkan bahawa suhu dan keliangan permukaan venir mempengaruhi penembusan perekat.

INTRODUCTION

Oil palm trunk (OPT) has great potential to be converted into value-added laminated wood products such as plywood, laminated veneer lumber (LVL) and parallel strand lumber (PSL) (Nordin et al. 2004, Sulaiman et al. 2009, Abdul Khalil et al. 2010, Jamaludin et al. 2010, Loh et al. 2011, Hoong et al. 2012). In the production of laminated products using OPT, the quality of bonding and gluing properties are important. Bond formation between adhesive and lignocellulosic or porous material such as wood or non-wood is important to determine the amount of adhesive penetration into a substance. OPT is a non-wood material. It is a porous material formed by mainly parenchymatous tissues, which are also known as spongy tissues. This anatomical feature influences adhesive penetration into OPT. In plywood manufacturing, one of the serious problems is the high adhesive consumption due to the rougher surface of OPT veneer (Loh et al. 2011). Increase of adhesive penetration will at the same time increase adhesive application. This will add unnecessary cost to producing OPT panels. Therefore, it is necessary to study the adhesive penetration of OPT mainly veneer which is used to produce LVL.

The most common method used by researchers to study adhesive penetration into lignocellulosic material is adhesive penetration. Penetration of adhesive into the porous network of wood cells influences bonding strength between wood and adhesive (Marra 1992, Sernek et al. 1999). Many studies have been done on the penetration or diffusion of polymer solution and dispersion into wood and porous substrates (Mader et al. 2011). Apart from adhesive penetration, the spread of adhesive on the surface of wood is another important parameter. Adhesive penetration is reported to be related to mechanical interlocking mechanism (Shi & Gardner 2001). In addition, covalent bondings and secondary interactions such as Van der Waals forces and hydrogen bond are also important mechanisms in the adhesion theory (Marra 1992, Johns 1989).

Adhesive penetration is strongly affected by wood properties. Important wood properties are structure, permeability, porosity, surface roughness, surface energy, temperature, pressure, time and cell wall moisture content. Wood properties are found to influence the direction of adhesive penetration (Marra 1992, Rowell 1996). Adhesive penetration also depends on molecular size and viscosity of the adhesive (Scheikl & Dunky 1998). Studies on cellular form and diameter concluded that early wood exhibited better wettability and consequently better bonding than late wood (Scheikl & Dunky 1998, Shupe et al. 1998).

Fluidity of waterborne thermoset adhesives such as urea formaldehyde (UF) and phenol formaldehyde (PF) is largely dependent on flow properties imparted by the wood moisture. Molecular weight distribution of the solidity of adhesives, extender content, filler content and pH have been reported to influence the fluidity of these adhesives (Sernek et al. 1999). Most wood adhesives contain water as carrier. They do not wet properly because they need a substrate to improve on fluidity and assist in adhesion. The substrate should be a solid as it is one of the basic requirements for good adhesion. The surface of the substrate should be treated to ease adhesive spread and penetration. Treatment can be done by planing or sanding the surface 24 hours before application of adhesive (Vick 1999). Pre-treatments are to expose fresh surface and improve bonding between the adhesive and wood (Aydin 2004).

The process of producing veneer such as peeling can also influence adhesive penetration. Vázquez et al. (2003) studied the influence of rotary peeling on the presence of tight and loose sides of *Eucalyptus globules* veneer. The large surface alterations of the loose sides indirectly reduce the mechanical strength of veneer and allow greater adhesive penetration. Greater adhesive penetration causes high percentage of wood failure, which indicates good interfacial bonding between the veneer and adhesive in the plywood. The interfacial bonding is considered weak if the wood failure percentage is low. Veneer roughness is reported to influence adhesive bond quality, while bond quality is measured using percentage wood failure and load at failure (Neese et al. 2004). Regardless of conditions, bond failure occurs mostly on the loose side of the veneer (Neese et al. 2004).

There are many methodologies used by researchers to study adhesive penetration. Sernek et al. (1999) studied the penetration of UF adhesive in beech wood using an epi-fluorescence microscope. Ahmad (2000) used the same technique to evaluate penetration of PF adhesive and polymeric dipenylmethane diisocyanate in Calcutta bamboo. Johnson and Kamke (1992) used fluorescence microscopy to quantitatively analyse the gross adhesive penetration in wood. The techniques used by Sernek et al. (1999) and Ahmad (2000) were adopted in this study to determine the adhesive penetration in OPT veneer. The fluorescence microscopy uses a microscope that has very bright light source (ultra violet, blue, yellow or red light) which is then used to energise the specimen on the microscope stage (which may or may not be stained). In turn, the specimen will re-emit light at various wavelengths which then pass through the eyepieces. This technique proves that both spectroscopic and microscopic analyses are important tools in understanding the adhesive bond formation and failure.

MATERIALS AND METHODS

Materials

OPTs were obtained from Pelam Plantation in Kedah. The average green moisture content of the OPTs was 200–300%. The OPTs were cut into billets of dimension 24 cm, which were obtained from three different portions of the trunk. They were then peeled to form veneer using a chuck peeler machine. Adhesives used in this study were PF adhesive formulated for water boiling proof plywood and UF adhesive formulated for moisture resistant plywood.

Manufacture of laminated OPT veneer

The OPT veneer was cut into dimensions of 30.5 cm × 30.5 cm. The veneer was dried to a moisture content of 9 to 10% using an oven.

The thickness of veneer ranged from 3 to 4 mm. Three sheets of veneer were selected. The veneer surfaces were sanded using 220-grid sandpaper and compressed air was blown onto the surfaces to remove dust and loose fibres. The adhesive was applied onto the veneer surface using hand brush. The volume of adhesive applied was 431 g m^{-2} for PF and 377 g m^{-2} for UF. The veneer was arranged one above the other and parallel to each other (Figure 1). The veneer layers were then pre-pressed to allow for tacking of adhesives to the arranged veneer and to assist in spreading the adhesive throughout the veneer surfaces for better interfacial bonding. The evenness of the adhesive spread could be assessed manually by looking at the adhesive squeezed out along the glue lines. The glued LVL was further segregated into three groups. Each group of LVL was applied with different pressing temperatures, i.e. 115, 125 and 135 °C. The LVL was hot pressed with a pressure of 10 kg cm^{-2} to 9 mm thickness. One LVL was pressed at a time. The hot pressing durations were as follows: 125 °C/PF = 690 s, 130 °C/PF = 630 s, 115 °C /UF = 530 s and 125 °C/UF = 430 s. A total of 32 LVL were left to cool to encourage adhesive curing before conditioning in a chamber at 16 °C and 65% relative humidity. The boards were later cut into standard size for adhesive penetration test.

The procedures for specimen preparation were adopted from Ahmad (2000) and Sernek et al. (1999). Specimens were selected randomly from the LVL manufactured using PF and UF adhesives. Specimens were cut into dimensions of 2 cm × 2 cm and submerged in water placed in a conical flask for 2 hours. A vacuum pressure was applied to the specimens for 2 hours to remove air in the specimens. Specimens were then sliced using a microtome to obtain transverse sections of 50 µm (Figure 1).

Only the specimen glued with UF adhesive was set in 0.5% Toluidine Blue O solution for at least 5 min. The sections were then rinsed in distilled water, soaked in 70% ethanol and subsequently in 100% ethanol. The soaked sections were then mounted on microscope slides using glycerine. The slides were observed using a microscope. Toluidine Blue O suppressed the auto-fluorescence of the OPT veneer. The adhesive appeared blue in colour whereas OPT veneer, black. Specimens glued with PF adhesive were prepared and observed with similar procedures as those glued with UF adhesive. However, specimens treated with PF were not applied with Toludine Blue O solution prior to observation. The images captured were in original colour. The adhesive was presented in reddish-brown colour. Images were captured using a digital camera. All images were processed and analysed using video test image analysis software. Measurements assessed were effective penetration (EP), average penetration (AP) and maximum penetration (MP). A graphical explanation is given in Figure 2.

EP is the total area of adhesive detected in the interphase region of the glue line divided by the width of the glue line. AP is the average distance of penetrations obtained from six deepest adhesive penetrations detected. MP is the maximum penetration depth detected. It is measured at the maximum edge of the adhesive penetrated into the veneer. In the image, the cured adhesives were highlighted manually to differentiate the cured adhesive from the OPT veneer background. The area of the highlighted objects and the maximum penetration were then

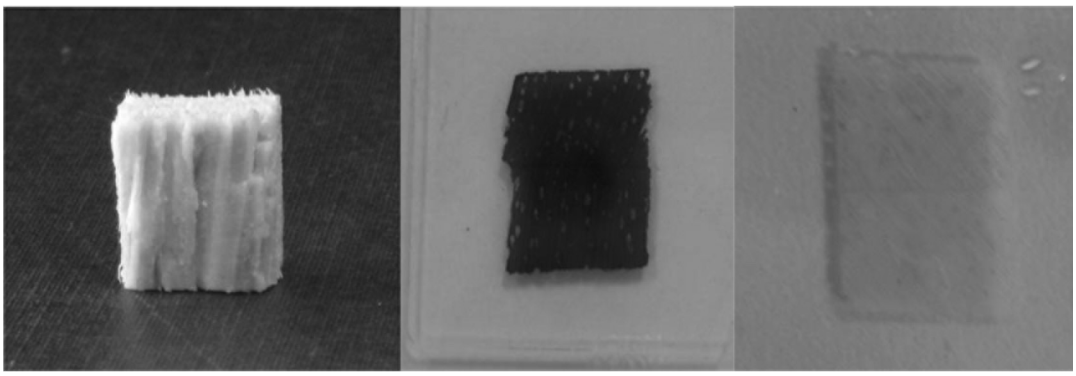

Figure 1 Specimens for evaluating adhesive penetration properties

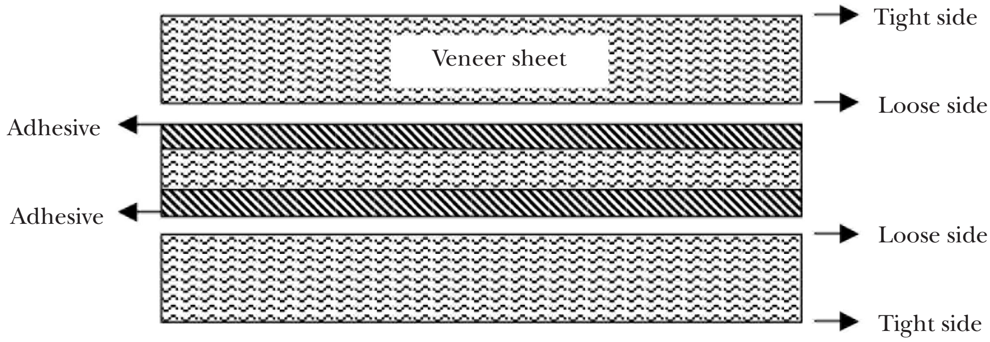

Figure 2 Laminated veneer lumber lay up

measured using the digital image processing and analysis software. The EP and MP were calculated using the formula by Sernek et al. (1999).

$$EP = \sum_{i=1}^{n} A_i / x_o \quad (1)$$

where A_i = area of cured adhesive (µm), n = number of cured adhesive and x_o = width of the maximum rectangle defining measurement area (1297 µm).

$$MP = \sum_{i=1}^{5} (y_i + r_i - y_o) \ / \ 5 \quad (2)$$

where y_i = centre of the cured adhesive, i = one of the five deepest penetrations of cured adhesive (µm), r_i = mean radius of object i and y_o = reference y-coordinate of the glue line interface (µm).

AP was calculated following the formula of Ahmad (2000).

$$AP = \sum_{i=1}^{3} (y_i) \ / \ 3 \quad (3)$$

where y_i = distance of the farthest edge of the three deepest penetrations of cured adhesive from the surface. Conversely, the present study used six distances of farthest edge adhesive to evaluate the AP. Ahmad (2000) simplified the formulation for MP to:

$$MP = y_{max} \quad (4)$$

where y_{max} = farthest edge of the deepest adhesive penetration from the surface.

The width of the maximum rectangle defining the measurement area (x_o) was 3467 µm, while the distance of the farthest edge (y_i) indicated the average of six deepest adhesive penetrations from the surface. The data were analysed using two-sample t-test via analysis of variance (ANOVA).

RESULTS AND DISCUSSION

Figures 3 to 5 show that adhesives penetrated into parenchymatous ground tissues, vessels and parenchyma around the vascular bundles of the veneer. However, adhesives did not penetrate into fibrous tissues. This could be due to the thin-walled spherical cells of the parenchyma which permitted adhesive penetration to occur more actively than fibrous tissue in the vascular bundles. The figures showed that cured glue lines for PF and UF adhesives were easily recognised with colour inversion and fluorescent lamp.

Effective penetration

The EP results for PF adhesive (Table 1) were significantly affected by portions ($p = 0.001$) and veneer parts for both top and bottom portions ($p < 0.05$) but not affected by pressing temperature. This could be due to the presence of vascular bundles and parenchymatous tissues as reported by Lim and Khoo (1986). They also found that the density of vascular bundles at the bottom part of an OPT was higher than the top. Since vascular bundles at the bottom part was denser, a lower adhesive penetration was expected. This conformed to the results obtained whereby adhesive was observed to penetrate more into the parenchyma tissues around the vascular bundles than into the vascular bundles. This shows that the anatomical features of the OPT veneer influence the EP. In another related study, Sernek et al. (1999) reported that anatomical features contributed significantly to EP between wood directions and portions of beech.

EP results for UF adhesive (Table 1) showed that the hot pressing temperature significantly influenced EP values at $p = 0.001$. However, EP

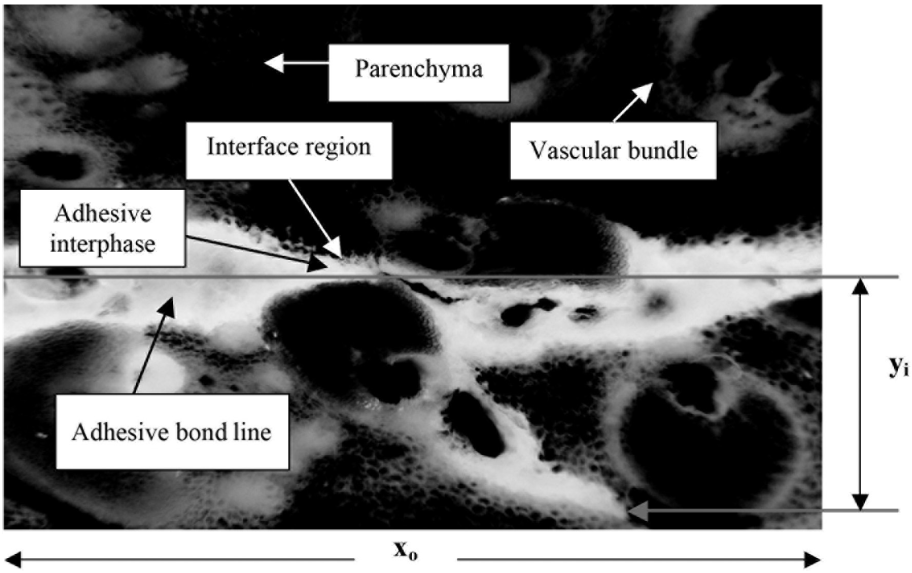

Figure 3 Adhesive penetration in oil palm trunk veneer to explain the dimensions used for measuring effective penetration, average penetration and maximum penetration

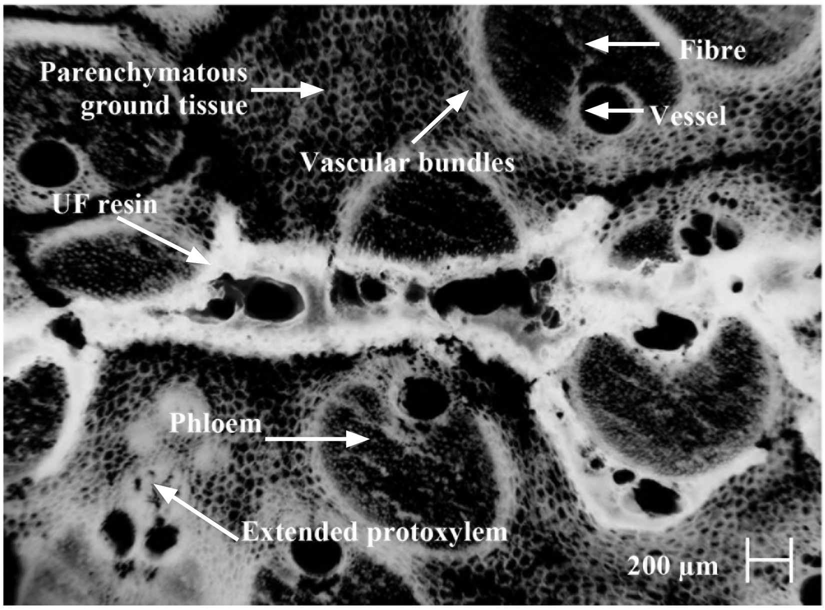

Figure 4 Bond line of phenol formaldehyde adhesive on transverse plane of laminated oil palm trunk veneer

values for veneer taken from different portions and parts at the top and bottom portions showed no significant difference. EP results indicated that hot pressing at the 115 °C gave higher adhesive cure per area than 125 °C. This significant difference may be caused by water component in the adhesive. Water has been reported to influence the amount of adhesive penetration (Sernek et al. 1999). However, mean EP values revealed that adhesive penetration into veneer obtained from the bottom portion (2510 µm) was higher than the top portion (2417 µm). EP values for veneer obtained from the top portion showed that the outer part (2420 µm) was greater than the inner part (2415 µm). For veneer taken from the bottom portion, EP value for the outer part (2455 µm) was lower than the inner part (2566 µm).

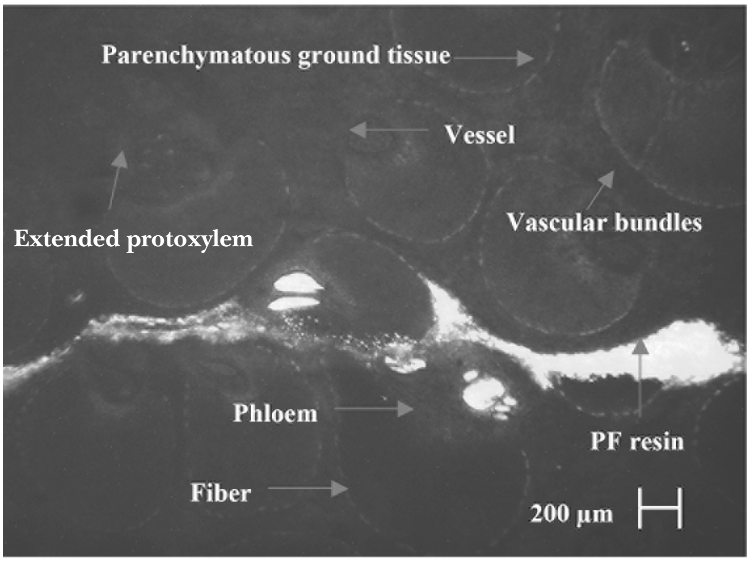

Figure 5 Bond line of urea formaldehyde adhesive on transverse plane of laminated oil palm trunk veneer

Table 1 Analysis of variance and mean values for adhesive penetration properties of phenol formaldehyde and urea formaldehyde in laminated oil palm trunk veneer at different curing temperatures, trunk portions and veneer parts

Source of variation	n	PF adhesive			UF adhesive		
		EP (µm)	AP (µm)	MP (µm)	EP (µm)	AP (µm)	MP (µm)
Curing temperature (°C)	112	ns	*	ns	***	**	**
115		–	–	–	2706	896	1268
125		4405	1068	1393	2221	845	1323
130		4287	1046	1405	–	–	–
Trunk portion	112	***	***	ns	ns	ns	ns
Top		4592	1011	1406	2417	877	1283
Bottom		4100	1102	1393	2510	864	1307
Veneer part (top)	56	*	***	***	ns	***	***
Outer		4800	1047	1431	2420	932	1354
Inner		4384	1114	1380	2415	822	1213
Veneer part (bottom)	56	*	*	ns	ns	*	*
Outer		4384	975	1394	2455	833	1271
Inner		3924	1091	1391	2566	895	1344

ns = Not significant, * significant at $p \leq 0.05$, ** significant at $p \leq 0.005$, *** = significant at $p = 0.001$; EP = effective penetration, AP = average penetration, MP = maximum penetration; PF = phenol formaldehyde, UF = urea formaldehyde; n = number of sample

Average penetration

AP results for PF adhesive from different portions and parts of the top portion showed highly significant difference at $p = 0.001$. Comparisons between temperature and part at the bottom portion were significantly different at $p < 0.05$. The significance between hot pressing temperatures showed that temperature influenced the AP of the liquid adhesive in laminated OPT veneer. The significance between trunk portions could be due to parenchyma tissues retaining the bulk of the adhesive so that the adhesive penetrated deep into the top portion, where denser parenchyma tissues existed. Due to better surface smoothness of the outer part, the adhesive penetrated more easily into the parenchyma tissue than into the inner part. Adhesive flow and penetration into wooden surfaces have been reported to be significantly affected by roughness (Scheikl & Dunky 1998, Aydin 2004). The surface of the outer part of OPT was much smoother than the inner part because the inner part contained denser parenchyma tissues which made the surface rougher. The rough surface affected adhesion and made adhesive penetration easier.

The AP results of UF adhesive into veneer from parts of the top portion of the trunk were highly significant ($p = 0.001$) compared with those taken from the bottom portion. Hot pressing temperatures and trunk parts influenced AP results between temperatures at $p < 0.005$ and between parts at the bottom portion at $p < 0.05$. However, trunk portions did not influence the results. Hot pressing temperature has been reported as one of the process-related factors to influence adhesive penetration (Sernek et al. 1999). One of the parameters that influence penetration of liquid adhesive into porous substrates is permeability. It significantly influences penetration of liquid into wood during impregnation due to its structure (wood species), location in the trunk, grain direction, size of cellular elements as well as moisture content, degree of degradation and air content in the structure (Kučerová 2012).

Maximum penetration

MP was measured at the deepest tip of the cured adhesive. MP values of PF adhesive for veneer taken at different parts of the top portion of the trunk was highly significant ($p = 0.001$), while those at the bottom portion were not significantly different. MP at hot pressing temperatures of 125 and 130 °C were 1393 and 1405 μm respectively. The veneer obtained from the top portion (1406 μm) of the OPT exhibited MP values not significantly higher than those from the bottom portion (1393 μm). MP results between outer and inner parts showed that penetration increased outwards from the core to the periphery region. The significant difference between MP values of the outer and inner parts of the top portion might be influenced by pH values of both parts, due to the difficulty of the PF adhesive to spread on the veneer of the top portion compared with the bottom. Based on a preliminary study, it was found that the top portion of OPT had pH 4.52 but the PF adhesive had a higher pH, 12.6. Due to this, PF adhesive cured faster before it could penetrate deep into the veneer (Atta-Obeng 2011).

MP of UF adhesive cured at different temperatures was significantly different at $p < 0.005$. Trunk parts had high significant influence on the MP at the top ($p = 0.001$) and bottom ($p < 0.05$). However, trunk portion did not show significant influence on the MP. MP value at hot pressing temperature of 125 °C was higher than that at 115 °C. Adhesive properties of polymer for porous substrates have been reported to be affected by curing temperature (D'Amico et al. 2010). MP for the veneer from the bottom portion was higher than the top portion (1307 and 1283 μm respectively). Comparison at different parts of the top portion showed that the MP for the outer part (1354 μm) was higher than the inner part (1213 μm). Conversely, the different parts of the bottom portion revealed that the MP for the outer part (1271 μm) was inferior to the inner part (1344 μm).

CONCLUSIONS

Most EP and AP of PF adhesive were significantly affected by hot pressing temperature, OPT portion and veneer part. Comparisons of MP of PF adhesive showed that mean values were significantly influenced by veneer from the top portion at different parts. On the other hand, comparisons of EP, AP and MP of UF adhesive at different hot pressing temperatures and parts at both top and bottom portions were significantly different. There were no significant differences recorded for veneer from different portions. In conclusion hot pressing temperature, OPT portion and veneer part significantly influenced adhesive penetration. Generally, PF adhesive showed significantly superior adhesive penetration to UF adhesive.

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