Manufacture of Environmentally Friendly Plywood Bonded with Plastic Film

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Abstract

The main objective of this study was to evaluate the feasibility of using unmodified plastic film as a novel wood adhesive in the plywood production, which is done to eliminate formaldehyde release during plywood production and use. The bondability of plastic film was determined by testing the shear strength of plywood. In addition, physical–mechanical properties, including thickness swelling, water absorption, modulus of elasticity, and modulus of rupture under the optimal pressing conditions, were also considered. Results showed that the plywood could meet the requirements for Grade 2 plywood according to Chinese National Standard (GB/T 17657-1999) and that the highest strength was obtained under hot-pressing conditions (pressure, 0.7 MPa; temperature, 160°C; time, 1 min·mm^{-1}; and film dosage of two layers), which was comparable to that of commercial urea-formaldehyde plywood as determined by Liu (Master's thesis, Zhejiang Agric. and Forestry Univ., Hangzhou, China, 2010). Pressing temperature had a notable effect on adhesive penetration and bonded joints formed. Mechanical interlock, as observed by scanning electron microscopy, formed between nonpolar plastic film and porous poplar veneer.

Plywood is one of the most important wood-based panels with many advantages and has been widely used in diverse fields, including window frames, door frames, floors, and interior panels in cars. However, adhesives mainly used for plywood are largely formaldehyde-based materials, such as phenol-formaldehyde and urea-formaldehyde (UF) resins. Although these adhesives have the advantages of good adhesive properties and mature technology, the emission of formaldehyde in the production and use of plywood, especially resulting from the low resistance to hydrolysis of UF resin and some unreacted formaldehyde remaining in the resin, poses a great hazard to human health because formaldehyde is a human carcinogen (Sellers 2001; International Agency for Research on Cancer, World Health Organization 2004). As a result, there is an urgent need for developing formaldehyde-free wood adhesives. Significant efforts have been performed to reduce or replace the formaldehyde contents in adhesive formulations (Moubarik et al. 2009, Aqmar and ByungDae 2010, Jin et al. 2010, Ozalp 2011, YongSung and KyungHee 2011) or to develop adhesives from natural materials (Desai et al. 2003, Dias and Rocco 2004, Bono et al. 2010, Moubarik et al. 2010, Jang et al. 2011). Although some of these new adhesives have already been used in industrial applications, their supply is limited, which may be caused by the high modification cost and some of their inferior properties, for example, their poor water resistance.

On the other hand, plastic is widely used as useful packaging material almost everywhere in daily life. Nevertheless, it will become a pollution problem if it cannot be properly recycled. Early studies indicate that pure or recycled plastic powder has the advantage of unique adhesive performance when combined with wood fiber or wood powder (Beg and Pickering 2008, Faruk and Matuana 2008, Ashori and Nourbakhsh 2009, Crookston et al. 2011). However, research on combining wood veneer directly with plastic film by hot pressing is limited. Modified high-density polyethylene powder through in situ chlorinating graft copolymerization has been successfully used to manufacture exterior plywood (Tang et al. 2011, 2012). Low-density polyethylene film has also been chosen to develop nonformaldehyde plywood, and the resulting plywood meets the requirement for interior

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Forest Prod. J. 63(7/8):283–287.
doi:10.13073/FPJ-D-12-00062

plywood application (Chinese Patent 2000, Chang et al. 2009). Nevertheless, there is still a lack of data on the use of this kind of plywood in various applications. Therefore, further studies are necessary to decide whether plastic film can be directly used as an alternative adhesive in the wood industry.

In this study, disposable plastic films were selected as a thermoplastic-based adhesive to manufacture three-layer poplar plywood under different conditions by improved hot pressing. The effects of pressing temperature, pressing time, and spread volume on the adhesive shear strength of plywood were investigated. The objective of this investigation was to test the feasibility of unmodified plastic film as a novel adhesive to be combined with polar wood veneers. Not only can it increase economic and environmental value for the wood industry, but it can also become a viable substitute for formaldehyde-based resins plywood in the future with our further efforts.

Materials and Methods

Materials

Poplar veneers were provided by Zuo gezhuang (Hebei, China). The dimensions were 300 by 300 by 1.5 mm, and their moisture content was 4 to 6 percent. Plastic film purchased from Sunkor Company (Shanghai, China) was cut into the same dimension as veneer before being used as an adhesive. The main component of the plastic film used in the experiments is high-density polyethylene with a thickness of 0.05 mm per layer.

Manufacture of plywood

Three-layer plywood with dimensions of 300 by 300 by 4.5 mm was first assembled with opposing tight-side and loose-side veneers in all the glue lines and were stacked with the grain directions of the two adjacent veneers perpendicular to each other. Then the plywood was hot pressed under various manufacturing conditions (pressing temperatures, 150°C, 160°C, 170°C, and 180°C; pressing times, 0.5, 1, and 1.5 min·mm^{-1}; plastic film dosage ranging from one layer to four layers; and pressing pressure, 0.7 MPa). After hot pressing, the plywood was transferred to a cold press under a pressure of 0.7 MPa for 5 minutes at room temperature to reduce the distortion and stress of the plywood. Three replicate panels were manufactured for all the conditions.

Bondability of plastic film

Bondability of the plastic film bond line was determined by testing the shear strength of plywood. The resulting plywood was cut into small samples, as shown in Figure 1. At least 18 specimens of every condition were soaked in water at 63°C ± 3°C for 3 hours and cooled at room temperature for 10 minutes and then tested for shear strength in accordance with the Chinese National Standard (GB/T 17657-1999; Chinese National Committee for Standardization 1999), which can determine whether the plywood can be used in interior applications.

Modulus of rupture (MOR), modulus of elasticity (MOE), water absorption (WA; 24 h), and thickness swelling (TS; 24 h) tests of plywood manufactured under the optimal conditions were also conducted according to GB/T 17657-1999 and the results compared with those of traditional UF resin plywood as observed in a previous study (Liu 2010). Fifteen specimens for each test were used.

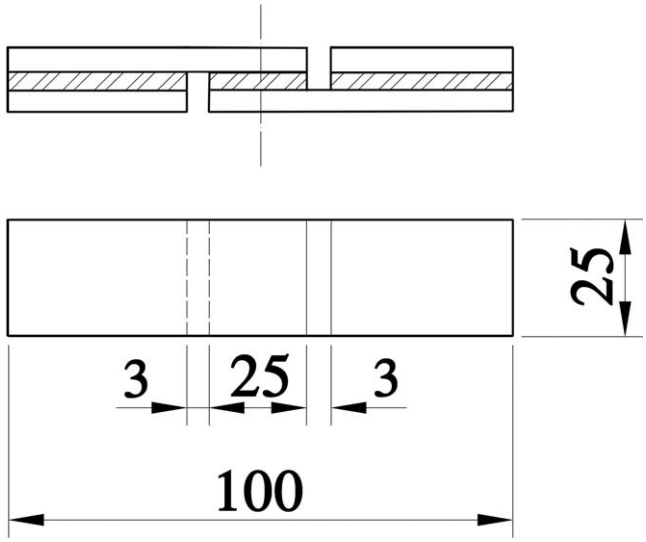

Figure 1.—Plywood sample for test of shear strength.

Mechanical properties were measured using a Multi-Function Mechanical Testing machine (Jinan Shijin Co. Ltd; 10 kN), with a crosshead speed of 5 mm·min^{-1}. Before testing, all samples were conditioned at 25°C and 65 percent humidity for 1 week.

Differential scanning calorimetric analysis

Differential scanning calorimetric analysis was performed using a DSC-60 Differential Scanning Calorimeter (Shimadzu Corporation, Japan). The sample of 5- to 10-mg plastic film in a flow of air was heated from 30°C to 220°C at a rate of 10°C·min^{-1}.

Viscosity of plastic film

Viscosities of the plastic film under different temperatures were tested by a CFT-500D Capillary Rheometer (Shimadzu Corporation, Japan). The diameter of the capillary was 1 mm.

Observation of bond line and bonded joints of plywood

An SZX 9 stereomicroscope was used to examine the mechanical bonding of the plywood. After a smooth surface of the plywood was prepared by a TU 213 slice machine, changes of bond line and bonded joints under different pressing temperatures were observed using a stereomicroscope.

Plywood interface morphology was also examined using an S-4800 scanning electron microscope at two different magnification factors (×150 and ×5,000). Samples were coated with gold to prevent charring during the microscopy.

Statistical analysis

SPSS 17.0 software was used to perform statistical analyses. Duncan's multiple range tests were used to determine the statistical difference among the variables investigated at the 95 percent significance level.

Results and Discussion

Characteristics of plastic film

Performance of the plastic film during processing played a great part in plywood quality. Flow and penetration of the plastic film into the porous structure of wood substrate was observed only when the pressing temperature was higher than the melting temperature. Figure 2 shows that the melting point of the film was 125.24°C, implying that the lowest level of temperature applied in our test should be no less than this value. Figure 3 illustrates the effect of temperature levels on the viscosity of plastic film. It can be seen that the viscosity of plastic film decreased with the increasing temperatures, which may greatly affect the strength of plywood prepared under different pressing temperatures. Therefore, four different temperatures (150°C, 160°C, 170°C, and 180°C) over the melting temperature were selected for good adhesive efficiency.

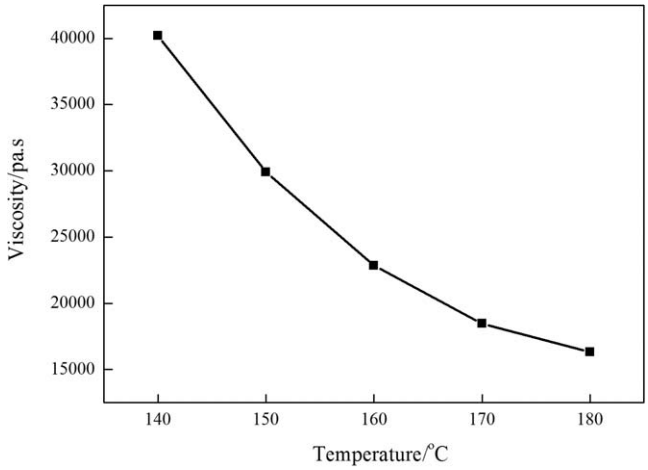

Figure 3.—Viscosity of plastic film as a function of temperature.

Effect of pressing temperature and time

Figure 4 shows the effects of pressing temperature and time on the shear strength of plywood. The obtained strength ranged from 0.91 to 1.14 MPa, all of which met the Chinese National Standard (GB/T 17657-1999) for Grade 2 plywood. The shear strength varied with the pressing temperature and time, as shown in Figure 4. When the pressing time was between 0.5 and 1 mm·min^{-1}, the shear strength of plywood improved as the hot-pressing temperature increased from 150°C to 160°C. However, shear strength slightly decreased when the temperature was raised from 170°C and 180°C at various pressing times. The highest shear strength was achieved at 160°C when the pressing time was raised to 1 mm·min^{-1}, and these optimal pressing conditions were used in the subsequent research. This result corresponded with the fact that pressing temperature and time have a synergistic effect on the shear strength of the resulting plywood.

Relationship between temperature and bonded joints and bond line

Stereomicroscopy was used to study penetration and bond line to further clarify why different shear strengths were obtained when plywood was manufactured under different pressing temperatures. Although the melted plastic film was able to penetrate into the veneer when pressed at 140°C, its fluidity was not good enough to move into the wood pores to form mechanically bonded joints and give a strong wood–adhesive bond (Fig. 5a). In contrast, a distinct bond line formed when the pressing temperature reached 160°C, at which point the plastic film developed suitable fluidity and viscosity (Fig. 5b) and therefore the highest shear strength.

An excessive decrease of viscosity also decreases strength with increasing temperature (Frihart 2005). As shown in Figures 3 and 5c, when the temperature increased to 180°C, the viscosity of the plastic film was 59.4 percent lower than that at 140°C, so discontinuous bond lines formed with too much of the adhesive moving into the veneer, causing starved joints and leading to a decrease in shear strength.

Effect of spread volume of plastic film

Figure 6 exhibits the shear strength of plywood bonded with different spread volumes in the wet state after immersion in water at 63°C ± 3°C for 3 hours. The values

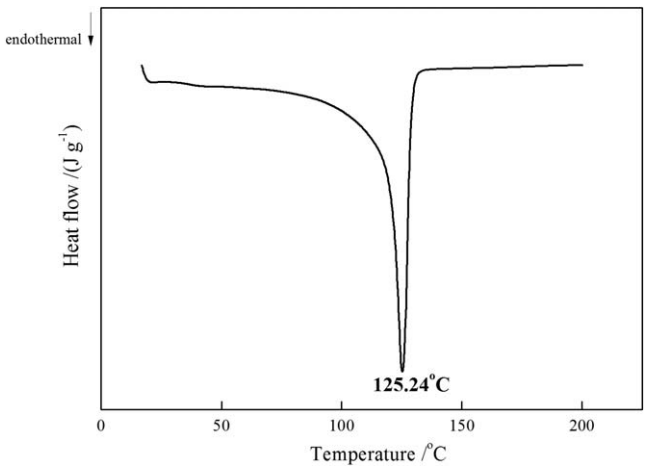

Figure 2.—Differential scanning calorimetric curves of plastic film.

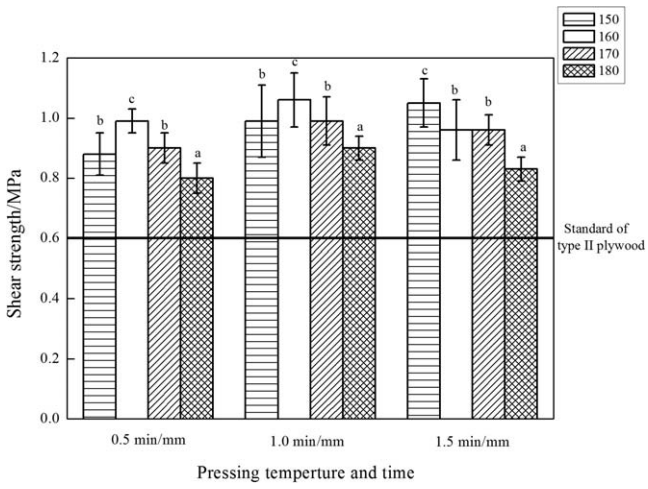

Figure 4.—Shear strength of plywood pressed at various pressing temperatures and times. Different lowercase letters denote a statistically significant difference (P < 0.05).

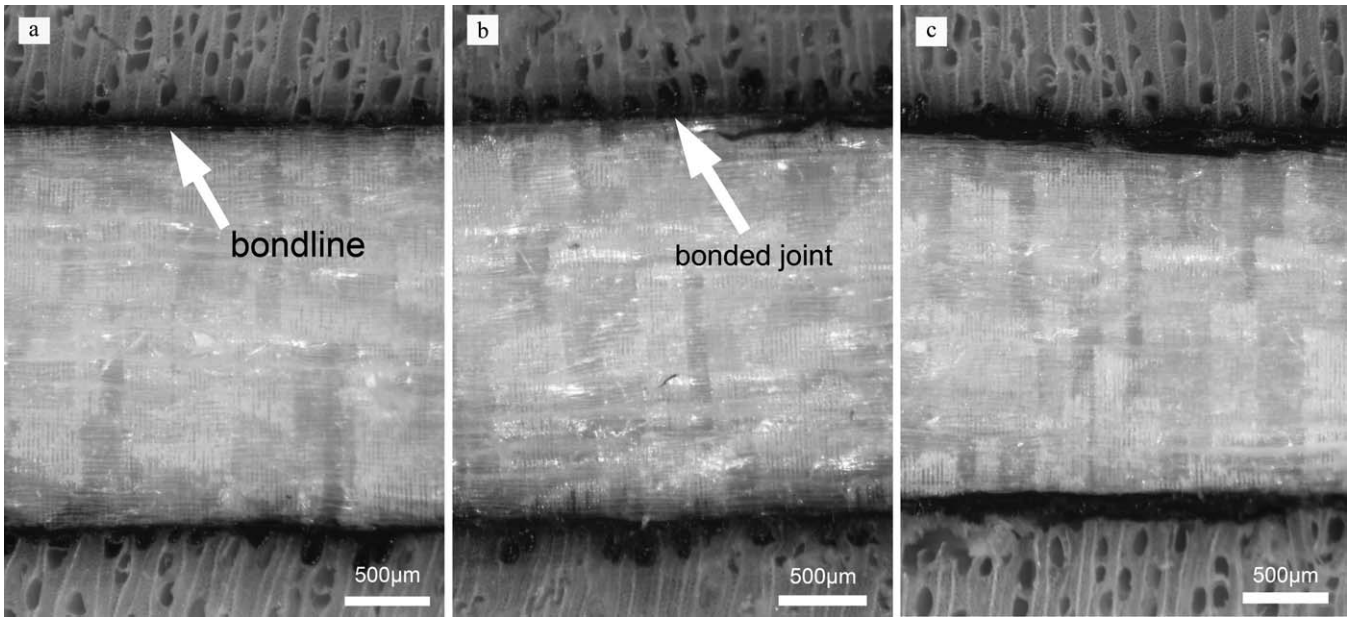

Figure 5.—Stereomicroscopic images of plywood pressed at different temperature levels: (a) 140°C, (b) 160°C, and (c) 180°C.

of shear strength were in the range of 0.91 to 1.15 MPa, and the highest shear strength was achieved when two-layer plastic films were used.

It is generally thought that the greater the spread volume of adhesives, the better the shear strength resulting from the sufficiently bonded joints between veneers. However, an excess of adhesive may lead to a thickening of the bond line and an increase in stress between veneers, causing a decrease in shear strength. Furthermore, the strength of plastic film itself is not very high, resulting in a further decrease in strength if the spread volume is too high.

Physical–mechanical properties of plywood

Table 1 reports the results of laboratory plywood prepared when using plastic film as an adhesive. The results indicate that formaldehyde-free plastic film adhesive gave MOR, MOE, and shear strength values that are comparable to those obtained with traditional UF resin as reported in a previous study (Liu 2010). In Table 1, the dimensional stability tests of WA and TS for plastic film gave values that were considerably lower than those observed for the traditional UF resin. This was attributed not only to the hydrophobic character of the plastic film because of its being devoid of functional polar groups such as hydroxyls, but also to the instability of the UF resin at high humidity since amino-methylene linkages are susceptible to hydrolysis.

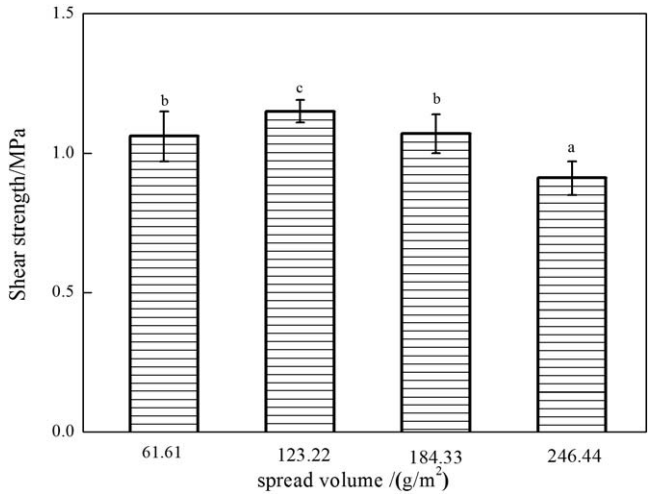

Figure 6.—Shear strength of plywood bonded with plastic film at various spread volumes. Different lowercase letters denote a statistically significant difference ($P < 0.05$).

Mechanism of plywood bonded with plastic film

It is theoretically acknowledged that the hydrophilic character of wood veneer and the hydrophobic character of thermoplastic are incompatible in thermodynamics and unsuitable for making plywood. Because wood is a porous material, mechanical interlock is the most likely bonding mechanism involved.

Figures 7a and 7b show the scanning electron microscopic images of poplar veneer bonded with plastic film at different magnifications. Such images can be used to explore the bonding mechanism of plywood qualitatively. Once passing the melting temperature of plastic film, the

Table 1.—Physical–mechanical properties of plywood panels prepared with plastic film adhesive compared with results obtained by Liu (2010) with traditional urea-formaldehyde (UF) resin.[a]

Adhesive type	Dry strength (MPa)	Wet strength (MPa)	MOR (MPa)	MOE (MPa)	WA (%)	TS (%)
Plastic film	1.8	1.15	62	6,424	60	8
UF resin	2.1	1.2	57	6,300	108	13

[a] MOR = modulus of rupture; MOE = modulus of elasticity; WA = water absorption; TS = thickness swelling.

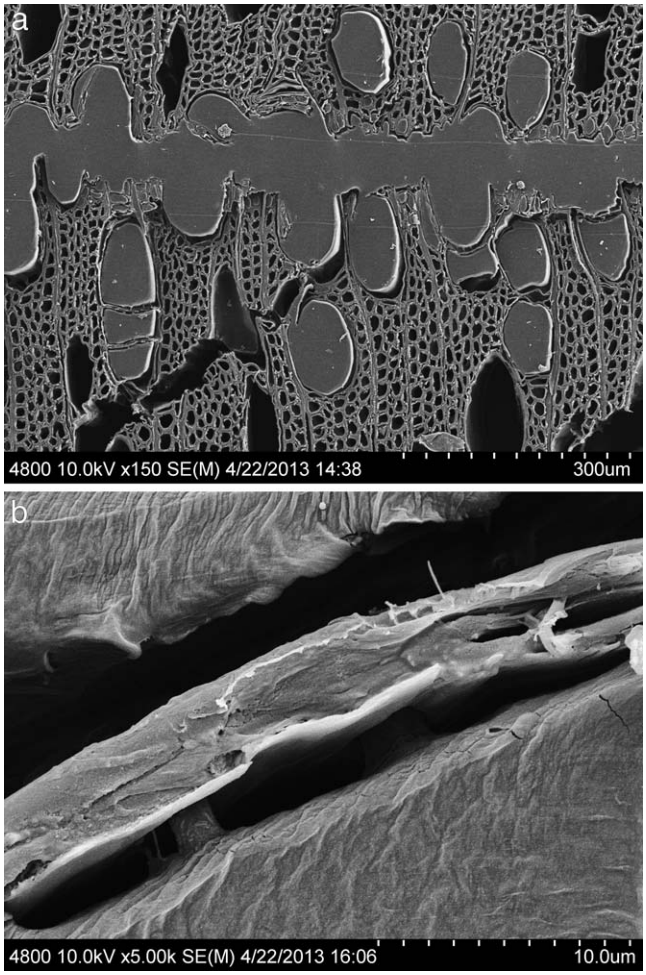

Figure 7.—Scanning electron microscopic images of poplar veneer bonded with plastic film: (a) ×150 and (b) ×5,000.

melted film wetted the substrate and penetrated into the vessel, so a mechanical interlock gave strength to the plywood.

It should be noted that wide gaps between the wood veneer and plastic film were observed along the interface of the two materials even at the optimal pressing temperature (Fig. 7b), an indication of poor adhesion of the plastic film to the wood surface. Therefore, further efforts, such as thermal treatment or silane modification on the veneer surface, should be made to improve the compatibility of the two phases and increase the mode of adhesion existing at the interface (Frihart 2005).

Conclusions

We have shown that it is possible to manufacture environmentally friendly plywood directly bonded with unmodified plastic film that can completely meet the requirement for Grade 2 plywood by the Chinese National Standard (GB/T 17657-1999). Mechanical interlock between polar veneer and nonpolar plastic can give plywood good performance for interior use as long as specific parameters, such as pressing temperature, time, and spreading volume, are controlled.

Acknowledgment

We gratefully acknowledge the financial support from ''Key Technology and Industrialization of Environment-Friendly Poplar Veneer Composites (201004004).''

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