# Investigation of Factory Fire Retardant Treatment of Eucalyptus Plywood

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## Abstract

Eucalyptus has become an important substitute material for the burgeoning plywood industry in China, whereas the corresponding fire retardant–treated products remain to be developed. This study preliminarily evaluated the feasibility of manufacturing fire retardant–treated eucalyptus plywood in the traditional industrial plant by veneer impregnation. *Eucalyptus saligna* and *Eucalyptus dunnii* veneers were impregnated by a commercial fire retardant at room temperature and atmospheric pressure. After redrying, the veneers were hot pressed into fire retardant–treated plywood in a conventional way. Fire performance was evaluated by cone calorimeter test. Basic properties (i.e., moisture content, bonding strength, and formaldehyde emission), mechanical properties (including modulus of rupture and modulus of elasticity), and hygroscopicity were also investigated. The fire retardancy of plywood was significantly improved by the fire retardant treatment, in terms of decreased heat release rate and increased residual mass fraction. The flame spread index values for plywood, which were calculated from the results from cone calorimeter tests, indicate that the fire performance of plywood improves from Class III to Class II after the treatment. The basic properties of fire retardant–treated plywood meet the requirements of GB/T 9846 (Standardization Administration of the People's Republic of China 2004). The mechanical and hygroscopic properties of fire retardant–treated plywood satisfy demands of general interior applications. The veneer treatment could be a suitable approach for Eucalyptus plywood factories to manufacture fire retardant–treated products.

The *Eucalyptus* genus, native to Australia, Indonesia, the Philippines, and New Guinea, has become the most commonly planted fast-growing hardwood around the world (Paine et al. 2011). Owing to the innovation both in technology and in business, the fast-growing eucalyptus, which shows price advantage and high mechanical performance, has been considered suitable as a new substitute for poplars or other traditional species to produce plywood in China during the last decade (Arnold et al. 2013). Although manufacturing first class plywood, which is regulated for structural or exterior uses, with eucalyptus veneers (Li and Xu 2012) or eucalyptus/poplar veneers (Wang et al. 2012b) has been demonstrated as feasible, eucalyptus plywood in China has been mainly manufactured for decorative or interior applications (e.g., parquet flooring and furniture). The flammability of this or other types of common plywood has limited their uses in public places or high-rise buildings, especially with the implementation of Chinese National Standard GB 20286-2006 (Standardization Administration of the People's Republic of China [SAC] 2006, Wang et al. 2010). Development of fire retardant–treated products is required to broaden the application of eucalyptus plywood in construction and decoration.

There are four main approaches to improve the fire retardancy of plywood: pressure treatment (Terzi et al. 2011), coating with fire retardant (Chuang et al. 2013), incorporation of fire retardants into the glue layers (Su et al. 1998), and veneer impregnation (Cheng and Wang 2011). Pressure treatment requires adhesives with high performance, complex equipment for vacuum-pressure treatment, and a long redrying process (Lee and Schaffer 1982, American Wood Protection Association [AWPA] 2012a). Although coating materials with fire retardant is able to reduce the surface flammability characteristics of wood

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This paper was received for publication in March 2014. Article no. 14-00020.

Forest Prod. J. 65(7/8):320–326.
doi:10.13073/FPJ-D-14-00020

products, there is still no general acceptance for using coatings to improve the fire resistance rating of a wood member (Ross 2010). Use of fire retardant glue is a convenient way for manufacturing flame retardant–treated wood-based panels, but plywood with limited quantities of fire retardant in glue does not meet strict flame retardant requirements (Chen et al. 2009). Therefore, veneer treatment, which requires a relatively simple production process and easily achieves the fire performance required, has become the optimal method for factories in China to produce fire retardant–treated plywood (Wang et al. 2011). The processes of veneer impregnation and plywood preparation have been studied with several fire retardants, followed by evaluation of basic properties and flame retardancy of plywood (Gu and Li 2004, Hu et al. 2008, Song et al. 2010). In these cases, veneer impregnation significantly improves the fire retardancy of plywood, while the basic properties of treated samples meet the requirements of the Chinese National Standard GB/T 9846 (SAC 2004). Furthermore, the effects of fire retardant treatment on surface roughness (Ayrilmis et al. 2006), mechanical properties (Ayrilmis and Winandy 2007), and bonding strength (Cheng and Wang 2011) of plywood are evaluated. However, most of this research was conducted in a laboratory, using samples with smaller dimensions than those used in commercial production. It is still not clear whether these results would be commercially viable for the production of fire retardant–treated plywood.

The main objective of this study was to investigate the performance of fire retardant–treated eucalyptus plywood prepared in a traditional plywood manufacturing plant using the method of veneer treatment. Moreover, the effects of fire retardant treatment on properties of plywood were evaluated. To achieve these objectives, two categories of eucalyptus (*Eucalyptus saligna* and *Eucalyptus dunnii*) were used to manufacture fire retardant–treated plywood in an industrial workshop. Flame retardant properties of the samples were evaluated by a cone calorimeter, which has become a convenient but effective method to assess the fire performance of wood-based materials (Lee et al. 2011, Terzi et al. 2011, Park et al. 2013). Moisture content, bonding strength, formaldehyde emission content, mechanical properties, and hygroscopicity of plywood were investigated according to relevant standards.

## Materials and Methods

### Preparation of fire retardant–treated plywood

The experiment was conducted in Shangsi Plywood Co., Guangxi Fenglin Wood Industry Group. The logs of *E. saligna* and *E. dunnii* (Table 1) were collected from Huangmian Farm, Guangxi Province, and were 7 to 18 cm in diameter and 1.3 m in length. The logs were then rotated to produce veneers that were 2.3 mm thick with spindleless lathes, followed by clipping to obtain 1,260 by 650-mm veneers (Sun et al. 2012). The veneers were dried by a continuous jet roller veneer dryer for about 10 minutes, with a final moisture content of 7 to 12 percent. Moisture content of veneers was measured by a portable moisture meter (with a range of 6% to 30%). This device transforms the electric resistance of veneers measured by two metal probes to moisture content of the samples, which is based on the quantitative relationship between these two parameters.

*Table 1.—Parameters of* Eucalyptus *used for experiments.*

| Species | Age (y) | DBH (cm)[a] | Height (m) | Basic density (kg $m^{-3}$) |
|---|---|---|---|---|
| *E. saligna* | 10 | 19–25 | 19–25 | 559.65 |
| *E. dunnii* | 10 | 17–19 | 14–21 | 584.70 |

[a] DBH = diameter at breast height.

An aqueous solution of one commercial fire retardant, with a concentration of 25 percent by weight and a pH of 6.50, was provided by Sheng Da Hua Yuan Company in Beijing. The fire retardant mainly consists of compounds containing phosphate and nitrogen, and the effectiveness of it is enhanced by a synergic effect of elements P-N-C-B-Al-Ti-Na. The dried veneers were immersed into the solution in a stainless steel tank at room temperature for 12 hours while laid vertically apart from each other. After impregnation, the veneers were redried with the same dryer, to a final moisture content of 7 to 12 percent. The average retentions of fire retardant (referred to as fire retardant divided by total weight of dry veneer) of *E. saligna* and *E. dunnii* were 4.50 ± 0.35 percent (27.57 kg $m^{-3}$) and 5.29 ± 0.58 percent (33.47 kg $m^{-3}$), respectively.

After joining two veneers into larger pieces with dimensions of approximately 1,260 by 1,300 mm, melamine urea-formaldehyde (MUF) resin with 54 percent solid content was evenly applied to the veneers with roller spreaders at a rate of 380 to 400 g $m^{-2}$ for one glue layer. Seven plies were assembled. After prepressing under a pressure of 0.73 to 0.87 MPa at room temperature for 1 hour, the prepressed fleeces were heat pressed into seven-ply plywood in multiple platen presses, using a pressure of 1.17 to 1.46 MPa at a temperature of 110°C to 115°C for 15 minutes. Finally, 15-mm-thick plywood samples measuring 1,220 by 1,220 mm were produced through trimming and sanding. A total of 20 panels, 10 for each species, were prepared. Meanwhile, another 20 pieces of plywood (10 for each species) were manufactured as control groups with the same production processes but without veneer impregnation. Three panels from each group were randomly selected for tests.

### Cone calorimeter tests

Cone calorimeter tests were carried out in the Beijing Technology and Business University using a Fire Testing Technology Cone Calorimeter, in accordance with the procedures indicated in the ISO 5660-1 standard (International Organization for Standardization 2002). The 100 by 100 by 15-mm specimens were irradiated with a heat flux of 50 kW $m^{-2}$. Three replicates of the specimens were tested.

Heat release rate (HRR), total heat release (THR), and time to ignition were collected by the computer connected to the cone calorimeter. In addition, the average effective heat of combustion (AEHOC) was calculated from the THR divided by the total mass loss for the duration of the test. Average mass loss rate (MLR) was calculated from the mass loss per unit of time over the time period from 10 to 90 percent of ultimate specimen mass loss divided by the sample area. Residual mass fraction was calculated as final mass divided by initial mass of samples.

### Moisture, bonding strength, and formaldehyde emission tests

Three 500 by 500-mm boards cut from each experimental panel were processed into samples for testing moisture content, bonding strength, and formaldehyde emission, according to the Chinese National Standard GB/T 9846 (SAC 2004). The size and number of samples for each panel are listed in Table 2. Moisture content was determined by the ovendrying method with a temperature of 103°C ± 2°C.

Bonding strength was measured by testing tensile shear strength of plywood using a universal mechanical testing machine (Jinan Time Group Inc., 10 kN; Cheng and Wang 2011). In total, three categories of specimens referring to and determining the bonding strength of all glue layers were sawed, as shown in Figure 1. The prepared specimens were soaked in hot water at 63°C ± 3°C for 3 hours and then cooled down at room temperature for 10 minutes. The two ends of the test specimen were fixed to a pair of clamp members fixed in the testing machine. Then the tensile force was applied at a rate of 5 mm $min^{-1}$ until it failed. The maximum failure load was recorded, and the tensile shear strength was calculated, which determines whether the plywood can be applied in interior conditions.

The formaldehyde emission from the plywood was determined by using a glass desiccator method in accordance with the Chinese National Standard GB/T 17657-1999 (SAC 1999). The desiccator method uses a common glass desiccator with a volume of 10 liters. Ten samples were placed in the desiccator. The formaldehyde, which is released from the samples during 24 hours at a temperature of 20°C, was absorbed in a crystallizing dish with 300 mL of distilled water and determined photometrically at 412 nm. The free formaldehyde emission was evaluated by the calibration curve of standard solution of formaldehyde with a slope of 0.2344 (concentration/adsorption, milligrams per liter).

## Mechanical properties tests

Modulus of rupture (MOR) and modulus of elasticity (MOE) of plywood were measured following the three-point bending test by the universal mechanical testing machine according to Chinese National Standard GB/T 17657-1999 (SAC 1999). The specimen measuring 350 by 50 mm was placed on two supports and loaded in compression at a rate of 5 mm $min^{-1}$ until it failed within 60 ± 30 seconds. MOR and MOE were automatically calculated by a computer. For each panel, three specimens were cut with their longitudinal dimension parallel to that of the outer veneer layer, and another three specimens were cut with their longitudinal dimension perpendicular to that of the outer veneer layer. Before testing, all samples were conditioned for 1 week at 20°C and 65 percent relative humidity.

## Hygroscopic properties tests

Hygroscopic properties of fire retardant–treated plywood were evaluated in accordance with the standard ASTM D3201-07 (ASTM International 2007a). Six specimens measuring 400 by 30 by 15 mm (volume of 180,000 $mm^3$) were prepared for each test panel, with their length parallel to the longitudinal direction of the outer veneer layer. After exposure to air (relative humidity within 30% to 65%) for 2 weeks, the weighed specimens were put into a CTHI-250B1 conditioning chamber (STIK Instrument Equipment Limited, Shanghai), which maintains a temperature of 27°C ± 2°C and a relative humidity of 92 ± 2 percent for 1 week. Then specimens were weighed again and placed in an oven at 103°C ± 2°C until two consecutive weight readings taken 2 hours apart varied less than 0.2 percent. The moisture contents of specimens before and after treatment were calculated.

*Table 2.—Size and number of samples from each panel for properties tests.*

| Test | Length (mm) | Width (mm) | No. of samples |
|---|---|---|---|
| Moisture content | 100 | 100 | 3 |
| Bonding strength | 100 | 25 | 18 |
| Formaldehyde emission | 150 | 50 | 20 |

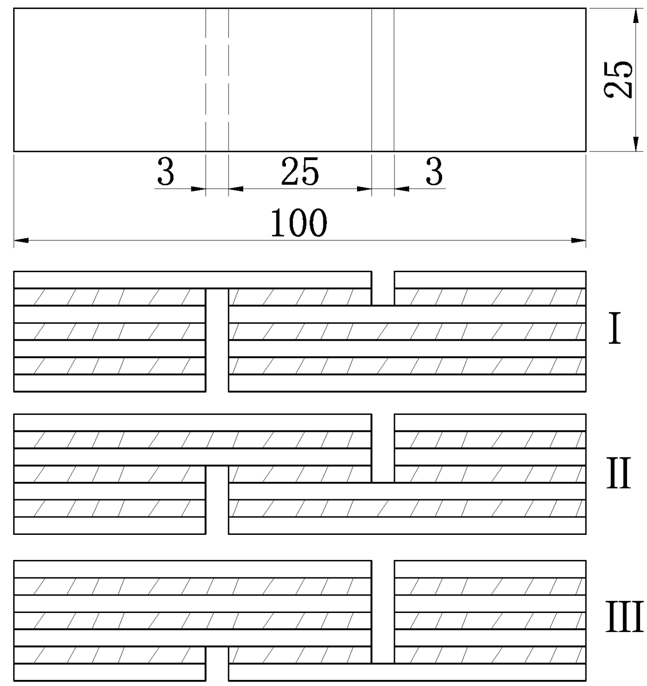


*Figure 1.—Profile of plywood specimens for tensile shear strength.*

# Results and Discussion

## Fire performance

The cone calorimeter is the most widely used small-scale fire test method, and this method is used in a great deal for the development of new materials (Grexa et al. 2003, Lowden and Hull 2013). The HRR data correspond directly to the intensity of fire, which is the main parameter in the cone calorimeter tests (Babrauskas and Peacock 1992, Terzi et al. 2011). Typical double-peak HRR curves were found for all four groups of plywood (Fig. 2). The first peak occurs after the ignition of the outer wood. The top of the peak for some samples split into two small peaks, possibly because of the layering structure of plywood (Wang et al. 2012a). Burning wood forms char, which could act as an insulating layer and hence slow down the heat transfer. The processes of thermal decomposition and volatile formation also diminish (Grexa et al. 2003). Therefore, shortly after the ignition the HRR decreases as the char layer forms, gradually reaching an approximately steady value. The steady periods for the treated *E. saligna* and *E. dunnii* samples were 620 and 630 seconds, respectively, 64.60 and 62.58 percent longer than untreated controls. The fluctuating

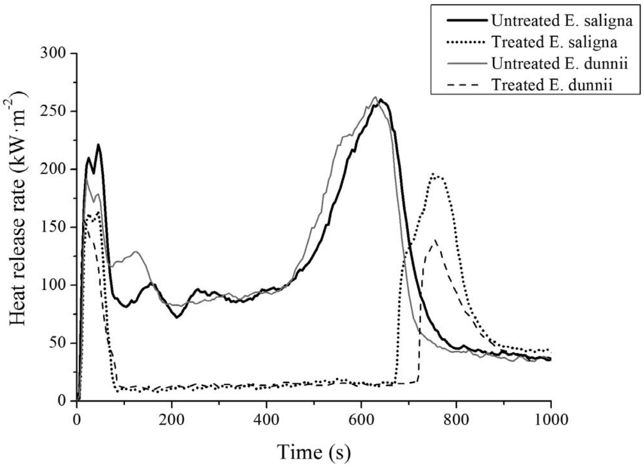


Figure 2.—Heat release rate curves of eucalyptus plywood in cone calorimeter tests.

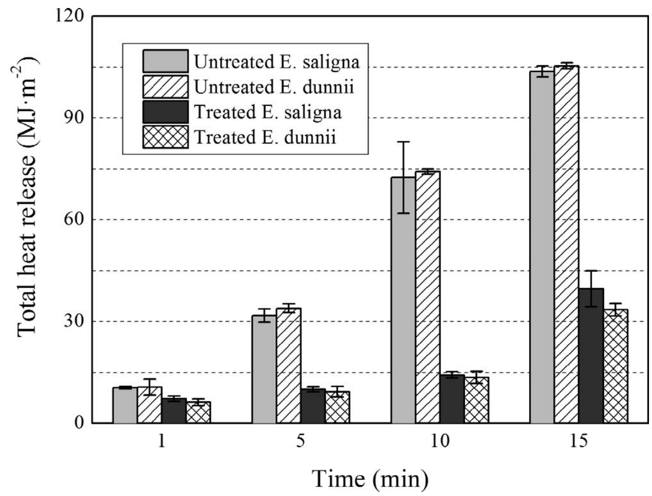


Figure 3.—Total heat release of eucalyptus plywood in cone calorimeter tests.

ranges of HRR during the steady period were 71 to 105 kW $m^{-2}$ and 75 to 128 kW $m^{-2}$ for treated *E. saligna* and *E. dunnii,* respectively, but only 8 to 20 kW $m^{-2}$ and 9 to 20 kW $m^{-2}$ for control samples. This probably suggests that the fire retardant enables plywood to form more stable char layers. The second peak in the curve is believed to be caused by sample burn-through and char cracking, facilitating the escape of more volatiles (Lowden and Hull 2013). The peaks and averages derived from the curves are presented in Table 3. Moreover, data of average MLR, AEHOC, and residual mass fraction were collected.

The fire retardant treatment significantly reduced average HRR (Table 3) and thus THR (Fig. 3). In 15 minutes, the THRs decreased by 64.09 and 71.91 percent for *E. saligna* and *E. dunnii,* respectively. Furthermore, the peak HRRs of the treated plywood were much lower than those of untreated plywood: 209 ± 18 kW $m^{-2}$ and 147 ± 4 kW $m^{-2}$ for the treated *E. saligna* and *E. dunnii* plywood compared with 275 ± 18 kW $m^{-2}$ and 268 ± 8 kW $m^{-2}$ for the untreated plywood. The second peak HRR appears about 2 minutes later for treated specimens. The results above indicate that the fire retardant treatments improve the fire retardancy of eucalyptus plywood. Meanwhile, the AEHOCs of the treated plywood were significantly lower than those of the control groups, which also implies better fire performance characteristics for the treated plywood (Terzi et al. 2011). Moreover, the treated plywood showed around 20 percent lower average MLR than untreated samples and over 1.5 times the residual mass fractions of control groups, which would likely be beneficial to keeping its structural stability in fire hazards (Wu and Harada 2005).

The cone calorimeter was also used to predict the flame spread index (FSI) in the tunnel test (Dietenberger and White 2001, White and Dietenberger 2004, Ayrilmis et al. 2007, Terzi et al. 2011), which is a regulatory test for surface flammability of building products in the United States (ASTM International 2007b). Dietenberger and White (2001) and White and Dietenberger (2004) have developed a predictive model in which initial peak HRR, THR, and time for sustained ignition from the cone calorimeter test are used to estimate the ASTM E-84 FSI. In the model, an acceleration parameter β is calculated from the initial peak HRR, an exponential time decay coefficient, and a material time constant (Table 4). Lower values for β indicate better fire performance. It can be seen that the β of

Table 3.—Test results from cone calorimeter test of Eucalyptus plywood.[a]

| Parameter | *E. saligna* Untreated | | *E. saligna* Treated | | *E. dunnii* Untreated | | *E. dunnii* Treated | |
|---|---|---|---|---|---|---|---|---|
| 1st peak HRR (kW $m^{-2}$) | 218 A | (10) | 162 B | (2.6) | 222 A | (42) | 147 B | (13) |
| Time to 1st peak HRR (s) | 30 A | (8) | 23 AB | (11) | 28 A | (11) | 10 B | (5) |
| 2nd peak HRR (kW $m^{-2}$) | 275 A | (18) | 209 B | (18) | 268 A | (8) | 145 C | (9) |
| Time to 2nd peak HRR (s) | 622 B | (37) | 740 A | (7) | 605 B | (28) | 728 A | (32) |
| Avg. HRR (kW $m^{-2}$) in: | | | | | | | | |
| 1 min | 174 A | (6) | 104 B | (14) | 178 A | (29) | 101 B | (19) |
| 5 min | 106 A | (7) | 33 B | (3) | 113 A | (4) | 31 B | (6) |
| 10 min | 121 A | (17) | 23 B | (2) | 124 A | (1) | 22 B | (3) |
| 15 min | 115 A | (2) | 43 B | (6) | 117 A | (1) | 37 B | (2) |
| Avg. mass loss rate (g $s^{-1}$ $m^{-2}$) | 12.3 A | (1.9) | 10.0 BC | (1.3) | 11.6 AB | (0.8) | 9.0 C | (0.6) |
| AEHOC (MJ $kg^{-1}$) | 11.9 A | (1.0) | 5.9 B | (1.7) | 12.6 A | (0.3) | 4.9 B | (0.3) |
| Residual mass fraction | 0.14 C | (0.02) | 0.27 AB | (0.03) | 0.22 B | (0.01) | 0.35 A | (0.03) |

[a] Within each row, values followed by the same letter are not statistically different at the $P < 0.05$ level of significance between samples according to Duncan's multiple range test. Numbers in parentheses are standard deviations. HRR = heat release rate; AEHOC = average effective heat of combustion.

*Table 4.—Model prediction derived from cone calorimeter of* Eucalyptus *plywood.*[a]

| Species | Treatment | Time to ignition (s) | Initial peak HRR (kW $m^{-2}$) | THR (MJ $m^{-2}$) | β (mg $liter^{-1}$) | Estimated FSI |
|---|---|---|---|---|---|---|
| *E. saligna* | Untreated | 20 | 218 | 107 | 0.264 | EUL |
| *E. saligna* | Treated | 16 | 162 | 47 | 0.137 | 55 |
| *E. dunnii* | Untreated | 25 | 222 | 109 | 0.254 | 115 (EUL) |
| *E. dunnii* | Treated | 23 | 147 | 39 | 0.062 | 39 |

[a] HRR = heat release rate; THR = total heat release; EUL = exceed upper limits of the logarithmic correlation between the ASTM E84-07 (ASTM International 2007b) flame spread index (FSI) and β, which is used to obtain the estimate of the FSI for one or more tests.

the treated plywood is significantly lower than that of the untreated control group. The β values for the two untreated species are similar, 0.264 mg $liter^{-1}$ for *E. saligna* and 0.254 mg $liter^{-1}$ for *E. dunnii*. However, the β value for the treated *E. dunnii* plywood is much lower than that of the treated *E. saligna* group. This value is also much lower than those of the birch–larch plywood treated with monoammonium phosphate (MAP) and diammonium phosphate (DAP; Terzi et al. 2011) .

The calculated β values are used to estimate the ASTM E-84 FSI (Table 4) and thus divide the test specimens into one of the three classes regulated in the US building codes to classify materials. A β of 0.184 is used to differentiate between Class III (FSI of 76 to 200) and Class II (FSI of 26 to 75) materials, while a β of 0 is used to distinguish between Class II and Class I (FSI of 25 or less). The untreated groups were rated as Class III like most other untreated wood products (White and Dietenberger 2004, Ayrilmis et al. 2007). However, the treated groups of both *E. saligna* and *E. dunnii* were classified into Class II, which further confirms the distinct improvement of fire performance for plywood due to the fire retardant treatment. In the study, no samples were rated as Class I, which is the most restrictive fire retardant treatment requirement of US domestic wood products. This is likely reflected in the relatively low retention levels (27.57 kg $m^{-3}$ for *E. saligna* and 33.47 kg $m^{-3}$ for *E. dunnii*) used in this study, because commercial fire retardants are typically used at retention levels between 32 and 80 kg $m^{-3}$ (Levan and Winandy 1990, Terzi et al. 2011).

## Moisture content, bonding strength, and formaldehyde emission

Moisture content, bonding strength, and formaldehyde emission are basic properties of plywood specified in Chinese National Standard GB/T 9846. It is important to examine whether the treatments have deteriorated the other properties of plywood products. It seems that the treatment can result in a slight increase in the moisture content (Table 5). However, the moisture content of all four groups of plywood ranged from 7 to 10 percent, which meets the requirement of 6 to 14 percent indicated in the standard. The treatment may also result in a reduction of tensile strength. The tensile shear strength of the four groups, with the minimum value of 1.23 ± 0.27 MPa and the maximum value of 1.78 ± 0.26 MPa, is much higher than the requirement of 0.7 MPa in the standard.

*Table 5.—Moisture content (MC), shear strength, and formaldehyde emission.*

| Species | Treatment | MC (%) | Tensile shear strength (MPa)[a] | Formaldehyde emission (mg $liter^{-1}$) |
|---|---|---|---|---|
| *E. saligna* | Untreated | 7.59 | 1.78 A (0.26) | 0.07 |
| *E. saligna* | Treated | 9.34 | 1.54 B (0.19) | 0.02 |
| *E. dunnii* | Untreated | 8.94 | 1.39 BC (0.20) | 0.34 |
| *E. dunnii* | Treated | 9.80 | 1.23 C (0.27) | 0.10 |

[a] Values followed by the same letter are not statistically different at the $P < 0.05$ level of significance between the samples according to Duncan' s multiple range test. Numbers in parentheses are standard deviations.

It is most interesting that the treatment resulted in a significant reduction of formaldehyde emission. For *E. saligna,* the formaldehyde emission was 0.07 mg $liter^{-1}$ for untreated and 0.02 mg $liter^{-1}$ for treated plywood. For *E. dunnii,* it was 0.34 mg $liter^{-1}$ for untreated and 0.10 mg $liter^{-1}$ for treated plywood. Formaldehyde emissions for all plywood tested were below 0.5 mg $liter^{-1}$, which indicates that the panels could be classified as class $E_0$ and could satisfy the demands of interior uses without further treatment to reduce formaldehyde release.

Compared with the fire retardant–treated poplar plywood prepared with similar manufacturing processes (Cheng and Wang 2011), the treated eucalyptus plywood showed a higher bonding strength and lower formaldehyde emission content. Eucalyptus could be a potential substitute for poplars to produce fire retardant–treated plywood.

Bonding performance of the treated plywood was lower than that of the untreated samples, probably because of chemical and surface changes of veneers during the treatment as observed in some previous reports on other plywood treatments (Cremonini et al. 1996, Cheng and Wang 2011). However, the reductions in shear strength were only 13.4 and 11.6 percent for *E. saligna* and *E. dunnii,* respectively, which are less than half the reduction of bonding strength for poplar plywood (Cheng and Wang 2011). In addition, as shown in Table 5, both untreated and treated *E. saligna* plywood exhibit significantly higher tensile shear strength than *E. dunnii* plywood groups. It may be a result of the better quality of *E. saligna* veneers, which show better moisture content uniformity and less veneer warp under the same drying process (Sun et al. 2012).

Free formaldehyde content in treated panels was found to be over 70 percent lower than that in control groups. Similarly, the decreases in formaldehyde emission were also observed in the treatment of poplar plywood with several fire retardants (Song et al. 2010, Cheng and Wang 2011). These reductions could mainly be attributed to the reaction of formaldehyde with fire retardants or chemicals like ammonia released from fire retardants during hot pressing. For normal plywood manufacturing, in order to decrease the formaldehyde emission in plywood without compromising bonding performance, the manufacturing plant usually has to add extra melamine while preparing MUF adhesives. It is apparent that less formaldehyde emission for fire retardant–treated plywood would benefit the plant in terms of reducing the melamine proportion in MUF resin and thus cutting the cost for producing adhesives.

## Mechanical properties

In addition to bonding strength, other mechanical properties are also important evaluation indexes for plywood, even for some nonstructural applications. China Forestry Industry Standard LY/T 1738-2008 (State Forestry Administration of the People's Republic of China 2008) requires the plywood for floor substrate to have a minimum MOR of 30 MPa and MOE of 3.50 GPa. The results (Table 6) show that the MORs of four groups of plywood exceeded 41 MPa and MOE exceeded 5.5 GPa. It is apparent that the treated eucalyptus plywood can be used for flooring and other nonstructural application areas where specific mechanical performance for wood products is demanded. The MOR and MOE values for the two eucalyptus species were higher than the reported Simul plywood (MOR of 26.91 MPa and MOE of 3.87 GPa) but lower than *Eucalyptus camaldulensis* plywood (MOR of 68.6 MPa and MOE of 7879 GPa; Nazmul et al. 2012).

The untreated *E. saligna* plywood presented the highest MOR of 54.5 MPa, while the treated *E. saligna* plywood displayed the highest MOE of 6.16 GPa. Mechanical properties of *E. saligna* plywood were better than those of *E. dunnii* plywood, except that MOEs of the two untreated groups were almost the same. This may be mainly due to the better bonding performance of *E. saligna* plywood. The effects of treatment on MOR and MOE of plywood were insignificant, although a slight reduction or increase of MOR and MOE was found during treatment. This is in contrast to the previous reports that state there are significantly adverse effects of common fire retardants (e.g., MAP) on plywood (Ayrilmis and Winandy 2007). The influences of fire retardant treatment on mechanical properties of plywood probably could depend on categories of fire retardant, fire retardant loadings, or even test methods (Ayrilmis and Winandy 2007).

## Hygroscopic properties

The hygroscopic properties of fire retardant–treated wood and wood-based products can be evaluated by exposing materials to high relative humidity following ASTM D3201 (Ostman et al. 2001). As shown in Table 7, both treated and untreated plywood showed a significant increase of moisture content during hygroscopic treatment as a result of the adsorption of wood or fire retardants while in the high relative humidity conditions. However, the water-based fire retardant gives rise to an increase in the hygroscopicity of plywood like ammonium bromide and DAP (Hirata et al. 1992), leading to the conclusion that the final moisture content of the treated plywood was about 5 percent higher than that of the untreated group. However, the final moisture content of all treated samples was far below 28 percent, which suggests that the fire retardant–treated products are suitable for applications where there is a specific need for use of materials of low hygroscopicity (AWPA 2012b). Therefore, the flame retardant–treated plywood would be suitable for interior applications, e.g., flooring, furniture, and ceilings, as far as hygroscopic properties are concerned. In addition, no significant differences were found in hygroscopic properties between *E. saligna* and *E. dunnii* plywood.

*Table 6.—Modulus of rupture (MOR) and modulus of elasticity (MOE) of* Eucalyptus *plywood.*[a]

| Species | Treatment | Basic density (kg m$^{-3}$) | MOR (MPa) | MOE (GPa) |
|---|---|---|---|---|
| *E. saligna* | Untreated | 679.63 | 54.5 A (17.59) | 5.88 AB (10.12) |
| *E. saligna* | Treated | 706.21 | 50.4 AB (18.97) | 6.16 A (9.96) |
| *E. dunnii* | Untreated | 704.13 | 44.0 B (20.73) | 5.83 AB (10.99) |
| *E. dunnii* | Treated | 738.50 | 41.5 B (12.75) | 5.57 B (14.28) |

[a] Within each column, values followed by the same letter are not statistically different at the $P < 0.05$ level of significance between samples according to Duncan's multiple range test. Numbers in parentheses are standard deviations.

*Table 7.—Change of moisture content in* Eucalyptus *plywood under hygroscopic tests.*

| Species | Treatment | Moisture content (%)[a] | |
|---|---|---|---|
| | | Before treatment | After treatment |
| *E. saligna* | Untreated | 7.90 | 14.67 |
| *E. saligna* | Treated | 9.24 | 19.04 |
| *E. dunnii* | Untreated | 8.13 | 14.55 |
| *E. dunnii* | Treated | 9.42 | 19.78 |

[a] Specimens were placed in the conditioning chamber maintained at a temperature of 27°C ± 2°C and a relative humidity of 92 ± 2 percent for 1 week. Before and after the treatment, the moisture contents of specimens were calculated.

## Conclusions

With additional veneer impregnating devices, both *E. saligna* and *E. dunnii* fire retardant–treated plywood were manufactured in a conventional industrial workshop. Treating veneer significantly improved the fire retardancy of plywood with a reduction of HRR and increase of residual mass fraction. The estimated FSI values for plywood suggest that fire performance of eucalyptus plywood improves from Class III to Class II owing to the fire retardant treatment. Moisture content, bonding strength, and formaldehyde emission content of fire retardant–treated plywood meet the requirements of the Chinese National Standard GB/T 9846 for general interior applications. Meanwhile, both mechanical and hygroscopic properties of fire retardant–treated plywood also satisfy demands of general interior applications. The veneer treatment methodology is feasible for eucalyptus plywood factories to manufacture fire retardant–treated products.

Compared with the untreated control group, the fire retardant–treated plywood has an 11 to 14 percent lower shear strength. However, the treated plywood shows over 70 percent lower formaldehyde emission than the untreated plywood. MOR and MOE are very similar between the treated and the untreated plywood, while the hygroscopicity was higher for the former than the latter.

## Acknowledgments

The authors gratefully acknowledge the financial support from the Chinese State Forestry Administration Project (the key technologies of eucalyptus plywood industry upgrade, 201104003-02). We also thank Shangsi Plywood Co., Guangxi Fenglin Wood Industry Group, for its generous assistance in our experiment.

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