Eco-Friendly Phenol–Urea–Formaldehyde Co-condensed Resin Adhesives Accelerated by Resorcinol for Plywood Manufacturing

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ABSTRACT: Eco-friendly and good-performance resin adhesives are needed for wood manufacturing. In this study, phenol–urea–formaldehyde (PUF) resin adhesives were modified by adding various ratios of resorcinol. The properties of PUF, phenol–resorcinol–urea–formaldehyde (PRUF) resin adhesives, and the performances of the prepared plywood were tested. The curing behaviors and the structural features of the PUF and PRUF resin adhesives were investigated via dynamic scanning calorimetry, thermal gravimetric analysis, $^{13}$C NMR, and cross polarization magic angle spinning $^{13}$C NMR. The results indicated that 1.3% resorcinol (based on resin, w/w) could decrease the curing temperature and accelerate the curing process after PUF resin modification. The PRUF resin adhesives demonstrated a lower activation energy during the curing process, with up to 28.8% less energy than that of PUF resin adhesive without any curing agent. The plywood demonstrated low formaldehyde emissions (<0.1 mg L$^{-1}$) and acceptably high bonding strengths (>1.00 MPa). This work provided a method for preparing an easy-cured and high-performance phenolic resin for wood manufacturing.

1. INTRODUCTION

Adhesives are vital ingredients for the manufacturing of wood-based composite panels, including plywood, oriented strand board, medium-density fiberboard, and laminated veneer lumber. Urea–formaldehyde (UF) adhesive, phenol–formaldehyde (PF) adhesive, and melamine–formaldehyde (MF) adhesive are the commonly used conventional thermosetting wood adhesives. The UF resin adhesive is a cheap and colorless adhesive that is typically used in an interior application. UF resin has poor water resistance and higher formaldehyde emission, which is harmful to human health and environment. The MF resin adhesive is more expensive, as it is water resistant and has good thermostability. This adhesive is ideal for exterior and semi-exterior use. The formaldehyde emission is lower compared with that of UF resin adhesive, but the curing temperature of the MF resin adhesive is relatively high. The PF resin adhesive creates strong bonds to resist solvents and aging, and is commonly used for large scale projects. This adhesive has a high curing temperature and a lengthy curing time during the manufacturing of wood panels. These three conventional adhesives each have their own defects that could be enhanced by modification.

Urea has partially replaced phenol when producing the co-condensed phenol–urea–formaldehyde (PUF) resin. The addition of urea to the PF resin significantly increases the reactivity and reduces manufacturing costs. The increased urea content would negatively affect the stability of the resin, which could result in poor water resistance and bonding strength. A few research studies have been reported about the additive amount of urea. The co-condensation between phenol, urea, and formaldehyde would cause a series of complicated reactions, which could affect the molecular structure of the resin, the curing process, and the performances of wood panels. Some PUF resin adhesives were modified by adding tannins. However, tannins with a high reactivity with formaldehyde and a large molecular size could result in a weak polymeric structure.

The carbonates and bivalent metal oxides have been shown as catalysts to accelerate the curing time for PUF resins. The wood bonding properties performed well at higher hot pressing temperature, which could ameliorate. Moreover, most of these inorganic salts and inorganic oxides demonstrate poor solubility or dispersity in aqueous phenolic resins, so the usage ratio of these resin additives remains relatively low. Furthermore, many additives for hardening acceleration were used in the glue mix, such as organic esters, carbonate, organic anhydrides, isocyanates, and aldehyde. The synthesis processes of resins with these additives were not studied.
ideal, resulting in the ordinary performances of the adhesives. These additives are effective but have not been applied on a large scale for wood panel manufacturing. Some research has focused on the nanoparticles, in an attempt to obtain a better reinforcement results, including nanofibrils,

The low solid content.26 The curing process of the soybean-based adhesive as a result of the adhesive was mostly under 37%. More energy was required for the curing process of the soybean-based adhesive as a result of the low solid content.26 Isocyanate adhesives were used as formaldehyde-free adhesives to demonstrate excellent bond performances in wood manufacturing.20 However, isocyanate is toxic to human health, which forces the factories to build a secure environment, resulting in expensive production costs.

Resorcinol is an aromatic compound (1,3-dihydroxy benzene) that is used directly in the synthesis of resin adhesives with phenol and formaldehyde. Only adhesives containing resorcinol have been used for some applications requiring ambient temperature setting or curing. This is due to the fact that resorcinol accelerates and improves the cross-linking of phenolic resin at low temperatures. The resorcinol-containing adhesives have good waterproof and durability performances.31 These phenol–resorcinol–formaldehyde resins are typically made by manufacturing a PF resin and then modifying it with resorcinol.32 The plywood that is glued with these cold-setting resin adhesives require lengthy pressing times exceeding 24 h.33

In this study, resorcinol was firstly used to marginally replace phenol during the synthesis process of co-condensed PF resins, to decrease the curing temperature and accelerate the curing of resins. The adhesive properties and the plywood performances were measured. To better understand the chemical structure, the curing behavior, and their relationship between the cure-accelerated phenol–resorcinol–urea–formaldehyde (PRUF) resins, the dynamic scanning calorimetry (DSC), thermal gravimetric analysis (TGA), 13C NMR, and cross polarization magic angle spinning (CP-MAS 13C NMR) were used to investigate the structural features and curing characteristics.

2. EXPERIMENTAL SECTION

2.1. Materials. Phenol (99%), formaldehyde aqueous solution (37%), solid urea (99%), sodium hydroxide (96%), and resorcinol (99%) were of analytical grade and were used without further purification.

2.2. Synthesis of PUF and PRUF Resins. The synthesis of the PUF and PRUF resins were performed in a round flask with three necks provided with a thermometer, a magnetic stirrer, and a reflux condenser. Phenol, urea, 37% formaldehyde water solution, and sodium hydroxide were prepared in the laboratory with a molar proportion of 1.0:1.2:3.2:1.2 via two-step reactions. In the first step, phenol and half of the formaldehyde were initially placed in the reaction flask, where 33.3% sodium hydroxide solution was gradually added to adjust the pH to 12 after constant stirring. The system was heated to 90 °C and maintained at this temperature for 40 min. A moiety of urea was blended into the compound and allowed to react for 1 h.

During the second step, the remainder of the formaldehyde and 33.3% sodium hydroxide solution were added to the compound. Resorcinol was a substitute for 0% (PUF) to 10% (PRUF) (w/w) of phenol, which meant the highest rate based on the resin was 1.3% (w/w). Resorcinol was slowly added under a temperature range between 80 and 90 °C. After a period, the temperature of the mixture was decreased to 65 °C, and the rest of the urea was blended into the compound for 30 min. The resulting resins were cooled to room temperature before use. Various reaction conditions performed are listed in Table 1.

| Table 1. Various Reaction Conditions of the PUF and PRUF Resins |
|-------------------|-------------------|-------------------|-------------------|
| resin             | resorcinol content (w/w) | time (min) | temperature (°C) | time (min) | temperature (°C) |
| PUF               | 0.0               | 100   | 90                  | 90   | 80                  |
| PRUF1             | 0.3               | 100   | 90                  | 90   | 80                  |
| PRUF2             | 0.7               | 100   | 90                  | 90   | 80                  |
| PRUF3             | 1.0               | 100   | 90                  | 90   | 80                  |
| PRUF4             | 1.3               | 100   | 90                  | 90   | 80                  |
| PRUF5             | 1.3               | 100   | 90                  | 70   | 90                  |
| PRUF6             | 1.3               | 100   | 90                  | 80   | 90                  |
| PRUF7             | 1.3               | 100   | 90                  | 90   | 90                  |
| PRUF8             | 1.3               | 100   | 90                  | 90   | 85                  |
| PRUF9             | 1.3               | 100   | 90                  | 150  | 85                  |

*Resorcinol content was based on resin, w/w.*

2.3. Three-Layer Plywood Manufacture and Testing. The performances of the PUF and PRUF resins were tested via preparing laboratory plywood and evaluating the formaldehyde emission and bonding strength in accordance with the Chinese National Standard (GB/T 17657-2013). Duplicate three-layer laboratory plywood panels (400 mm × 400 mm × 4.5 mm) were prepared using PUF or PRUF resin adhesives and poplar veneers without any curing agent. All these adhesives were mixed with 20% wheat flour as the filler. The glue spread was 316 g m−2 of double glue line, that was hot pressed for 243 s (54 s mm−1) or 405 s (90 s mm−1) at 135 °C, and with 1 MPa of pressing pressure. Following hot pressing, the plywood was stored in an ambient environment for 24 h prior to testing.

2.4. Dynamic Scanning Calorimetry (DSC). DSC analysis of the uncured freeze-dried adhesives was performed on a Shimazu DSC-60A (Japan) under a nitrogen atmosphere with a flow rate of 50 mL min−1. High-pressure aluminum hermetic pans, which could withstand vapor pressure up to 0.3 MPa, were used to prevent the components of the samples from evaporating at high temperatures. About 4 mg of the
samples were used in each test. Scans were run at heating rates of 5, 10, and 15 °C min⁻¹ and the scanning temperature ranged from 30 to 200 °C.

2.5. Thermal Gravimetric Analysis (TGA). Thermal stabilities of the cured PUF and PRUF resins were measured with TA Instruments TGA Q50 that operated from 25 to 700 °C at 10 °C min⁻¹. The PUF and PRUF resins were cured at 120 °C for 2 h to circumvent water adsorption. The nitrogen flow rate for all the samples was 60 mL min⁻¹. About 7 mg of the resin samples were used for each test in a platinum crucible. Curves of the weight loss and the derivative weight loss (differential thermogravimetry (DTG)) were plotted.

2.6. ¹³C NMR Spectra. Eighty milligrams of freeze-dried uncured adhesives were dissolved in 0.5 mL of D₂O for NMR shifts control for solution-state ¹³C NMR analysis. The spectra were obtained on a Bruker AV-III 400 MHz spectrometer (Germany). The cured adhesives were prepared by treating the uncured adhesives at 120 °C for 2 h in an air convection oven. The uncured and cured adhesive powders were packed into a zirconium oxide rotor sealed with a Kel-F cap for analysis. The acquisition time was 0.01 s with a number of transients, approximately 5000 for each experiment.

3. RESULTS AND DISCUSSION

3.1. Performances of PUF and PRUF Resin Adhesives. The PUF and PRUF resin adhesives with various ratios of resorcinol were all dark-brown aqueous solutions with excellent water solubility as shown in Figure 1. Table 2 presents in Table 3.

![Image](8523)

Figure 1. Image of the synthesized PRUF resin.

shows the solid content, the pH, and the viscosity of the PUF and PRUF resin adhesives. The formaldehyde emission and bonding strength of the plywood that was prepared under different bonding times were also characterized and are presented in Table 3.

The solid content and the pH of each PUF and PRUF resin adhesive met the requirements defined by the Chinese National Standard (GB/T 14732-2006). The viscosity of the PUF and some PRUF resin adhesives with a lower percentage of resorcinol accretion was less than the requirement of the Chinese National Standard (GB/T 14732-2006). It is well-known that controlling the viscosity of the adhesive has a great influence on its adhesion strength in wood panels. A low viscosity demonstrates a small molecular weight, which can result in a weak strength of plywood. The adhesives from PRUF4 to PRUF7 showed that both increasing the reaction time and the temperature could enhance the viscosity to reach the Chinese National Standard.

The formaldehyde emissions of all the plywood were below 0.5 mg L⁻¹ and reached the requirement of E₀ grade (≤0.5 mg L⁻¹) as specified by the Chinese National Standard (GB/T 9846.3-2004). The plywood prepared with the PRUF5 resin adhesive exhibited the lowest formaldehyde emission (0.01 mg L⁻¹). This plywood can be directly used in an interior application, which is beneficial to human health and inner environment. The bonding strength of the plywood bonded using PUF and PRUF resin adhesives met the requirements of the exterior-grade panels (first grade, ≥0.7 MPa) at a bonding time of 405 s. However, there was a weak bonding strength when the accretion of resorcinol was less than 1.3%. The actual result indicated that the plywood bonded with PURF5 to

Table 2. Adhesive Properties of the PUF and PRUF Resin Adhesives

| resin    | solid content (%) | pH (25 °C) | viscosity (22 °C, mPa s) |
|----------|-------------------|------------|--------------------------|
| PUF      | 44.95             | 12.79      | 37.8                     |
| PRUF1    | 45.52             | 12.76      | 54.6                     |
| PRUF2    | 42.54             | 12.81      | 40.8                     |
| PRUF3    | 43.99             | 12.91      | 54.0                     |
| PRUF4    | 43.72             | 12.9       | 166.8                    |
| PRUF5    | 44.37             | 13.2       | 94.2                     |
| PRUF6    | 45.14             | 13.14      | 334.7                    |
| PRUF7    | 44.81             | 13.2       | 350.9                    |
| PRUF8    | 44.42             | 13.13      | 46.2                     |
| PRUF9    | 44.09             | 13.17      | 164.4                    |

Table 3. Plywood Performances of the PUF and PRUF Resin Adhesives

| resin    | formaldehyde emission (mg L⁻¹) | bonding strength (MPa) |
|----------|---------------------------------|------------------------|
| PUF      | 0.03 (0.0072)                  | 1.01 (0.11)            |
| PRUF1    | 0.44 (0.03)                    | 0.51 (0.13)            |
| PRUF2    | 0.23 (0.0072)                  | 0.65 (0.09)            |
| PRUF3    | 0.25 (0.0018)                  | 0.89 (0.16)            |
| PRUF4    | 0.28 (0.0005)                  | 0.82 (0.12)            |
| PRUF5    | 0.17 (0.0027)                  | 0.95 (0.22)            |
| PRUF6    | 0.21 (0.0019)                  | 0.54 (0.16)            |
| PRUF7    | 0.13 (0.0027)                  | 1.04 (0.17)            |
| PRUF8    | 0.18 (0.0019)                  | 0.66 (0.10)            |
| PRUF9    | 0.01 (0.0011)                  | 1.11 (0.07)            |
| GB/T 17432-2006 | ≥0.50 (0.0038) | 1.12 (0.07) |

aStandard deviation.
Table 4. Thermal Cure Kinetic Parameters of the PUF and PRUF Resin Adhesives

| resin  | $T_p$ (°C) | curing temperature (°C)$^a$ | $E_k$ (kJ mol$^{-1}$)$^b$ | $E_l$ (kJ mol$^{-1}$)$^c$ |
|-------|----------|--------------------------|------------------|------------------|
|       | 5 °C min$^{-1}$ | 10 °C min$^{-1}$ | 15 °C min$^{-1}$ |                   |                   |
| PUF   | 144.3    | 153.0                    | 160.6             | 136.3 (0.9985)$^d$ | 94.9 (0.9884)  |
| PRUF5 | 143.9    | 153.3                    | 160.5             | 136.0 (0.9942)    | 93.0 (0.9954)  |
| PRUF6 | 139.0    | 152.9                    | 160.8             | 129.2 (0.9756)    | 67.6 (0.9995)  |
| PRUF7 | 141.2    | 151.7                    | 159.9             | 132.2 (0.9950)    | 81.1 (0.9947)  |
| PRUF8 | 139.3    | 153.2                    | 159.4             | 130.6 (0.9534)    | 72.6 (0.9927)  |
| PRUF9 | 141.5    | 153.1                    | 161.4             | 132.1 (0.9909)    | 76.0 (0.9979)  |

$^a$Curing temperature was calculated based on the linear regression analysis of the peak temperature over various heating rates. $^b$($E_k$ was calculated according to the Kissing method. $^c$($E_l$ was calculated according to the Flynn–Wall–Ozawa method. $^d$The values in parentheses represent the regression coefficients.

The characteristic curing temperature were determined by the peak temperature of the first exothermal peak obtained from the nonisothermal DSC measurements at various heating rates through linear regression analysis. The intercept at a heating rate of 0 °C min$^{-1}$ denoted the characteristic curing temperature under isothermal conditions.59,60 As given in Table 4, the characteristic curing temperatures of the PRUF resin adhesives were all lower than that of the PUF resin adhesive. The results turned out that the addition of resorcinol could reduce the curing temperature without any hardener agent.

The activation energy was calculated by the dependence of the peak temperature at various heating rates via the Flynn–Wall–Ozawa and Kissinger methods. The results are listed in Table 4.41 The $E_k$ values were similar to $E_l$ values. The regression coefficients were more than 0.98 for each of the regression calculations, which manifested credible and consistent results for both methods. The data in Table 4 indicated that the activation energy of the PRUF resin adhesives was lower than that of the PUF resin adhesive, which was in agreement with the variation of curing temperatures. The PRUF6 resin presented the lowest activation energy, which could reduce 28.8% more than the PUF resin. This reduction was likely due to the higher chemical activity of resorcinol with the two phenolic hydroxyls, which possessed strong electron-donor conjugated functions. The lower activation energy signified that the resin had an effortless curing process. Among PRUF resin adhesives, the PRUF6 exhibited the lowest curing temperature and activation energy, which demonstrated good bonding performances, as presented in Table 3.

3.3. Thermal Gravimetric Analysis (TGA) of PUF and PRUF Resins. The TGA and DTG curves of the cured PUF and PRUF resin adhesives are represented in Figures 2 and 3, respectively. These PRUF resin adhesives had different reaction temperatures during the second step. The temperature where the maximum degradation took place ($T_{\text{max}}$) in various thermal events of the cured PUF and PRUF resins, as well as the weight residues at 700 °C, are provided in Table 5. There were four main mass loss events during thermal degradation, which was more complicated with respective to those of conventional PF resins.42 The initial stage of weight loss between 200 and 322 °C corresponded to the post curing
reactions of the phenolic resin. The result was also confirmed by an endotherm in the DSC curves. The weight loss included the evaporation of water, formaldehyde, paraformaldehyde, phenol, and cresol. These formed via the condensation between the methylol groups, the breaking of the methylol groups, and the methylene bridge breakdown that lead to further crosslinking.\textsuperscript{34,43} Weight loss (13\textendash 15\%) of PUF and PRUF was observed at this stage, which could reflect the degree of the condensation reaction. There would be a drastic reaction at the maximum degradation temperature, as shown in Table 5. Generally speaking, the pressing temperature of the plywood panels should be set prior to the maximum ($T_{\text{max}}$ in the first stage). Among the PUF and PRUF resins adhesives, the PRUF6 and PRUF7 presented lower $T_{\text{max}}$ values than that of the PUF. This result validated that resorcinol could reduce the curing temperature.

The second and the third stage occurred in the temperature range between 322\textendash 365 and 365\textendash 450 °C, respectively. Degradation took place in these two steps and was thought to arise from the breakdown of methylene linkages and the loss of water that was produced from the condensation reaction between phenolic \( -\text{OH} \) and methylene and between the two hydroxyl functional groups. The ligand in the resin decomposed entirely into volatile products. The DTG of PRUF resins were visibly slower than that of the PUF resin displayed in Figures 2 and 3. There was a higher thermal stability during this stage. The fourth thermal event ranged between 450 and 588 °C. The crosslinking of the methylene with the carbon-hydrogen crosslinks led to hydrogen elimination with the formation of carbon monoxide and methane.\textsuperscript{34,43\textendash 45}

Table 5. Thermal Properties of the Cured PUF and PRUF Resin Adhesives

| resin | first thermal event $T_{\text{max}}$ (°C) | second thermal event $T_{\text{max}}$ (°C) | third thermal event $T_{\text{max}}$ (°C) | fourth thermal event $T_{\text{max}}$ (°C) | weight residue (%) |
|-------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|-----------------|
| PUF   | 276.5                           | 339.8                           | 391.0                           | 498.5                           | 53.6            |
| PRUF5 | 277.6                           | 323.3                           | 404.8                           | 510.0                           | 55.7            |
| PRUF6 | 273.0                           | 340.9                           | 380.6                           | 497.6                           | 55.8            |
| PRUF7 | 274.0                           | 342.0                           | 386.6                           | 497.0                           | 55.5            |
| PRUF8 | 278.9                           | 328.5                           | 386.4                           | 510.8                           | 55.5            |
| PRUF9 | 277.2                           | 322.3                           | 385.7                           | 510.9                           | 56.1            |

3.4. Solution-State $^{13}$C NMR of Uncured Resin Adhesives. The chemical structures of the PUF and PRUF resin adhesives were studied by employing a solution-state $^{13}$C NMR spectrum of the uncured adhesives after being freeze-dried. Figure 4 shows the $^{13}$C NMR spectra of the PUF and PRUF resin adhesives. The spectrum of the PUF resin adhesive was similar to those of the PRUF5 through PRUF9 resin adhesives. The series of peaks between 160.7 and 162.7 ppm are attributed to the urea’s $\text{C}=\text{O}$ groups in the branched resin spectra. The carbonyl peak at 161.0 ppm indicated that part of the urea did not react. In addition, the disubstituted

Figure 3. TG and DTG curves of the cured PUF, PRUF8, and PRUF9 resin adhesives.

Figure 4. Solution-state $^{13}$C NMR spectra of the uncured PUF and PRUF resin adhesives.
urea was of 162.7 ppm ($-CH_2-urea-CH_2$). The PUF and PRUF resins were synthesized with the beginning of the reaction between phenol and formaldehyde. Thus, the addition of a small quantity of urea reacted sufficiently to reduce the emission of formaldehyde in the final resin adhesives. The dominant signals around 127.6 ppm represent the free meta sites (C–H) and the para, ortho reacted sites (C–C) of the aromatic nucleus in resorcinol and phenol. The signals at 120
and 116 ppm, respectively, belong to the unreacted para, ortho sites (C−H) of the phenolic −OH in the aromatic ring, which was not observed previously.10 Thus, the para, ortho sites of the aromatic rings completely reacted with the resorcnil and phenol. Figure 4 shows that PRUF6 and PRUF7 resins had a weaker signal at 127.6 ppm compared with other resins. This is due to the fact that the meta sites were partially substituted when the resin is synthesized in a longer reaction time, as shown in Table 2. The chemical shifts of the formaldehyde from 80 to 100 ppm were not observed in Figure 4, indicating that the formaldehyde reacted sufficiently. Similarly, the signals from 71 to 76 ppm were also not observed. These signals are assigned to the methylene ether linkages which could break and release formaldehyde at high temperatures. Therefore, the PUF and the PRUF5 to PRUF9 resin adhesives had an extremely low formaldehyde emission, as shown in Table 3.

The peak at 61.5 ppm is attributed to the ortho methylol group of the phenol (o-Ph−CH2OH). The small signal at 46.3 ppm corresponds to the co-condensed methylene group (o-Ph−CH2−N(CH2−CO−), where the PRUF9 resin was slightly higher. The signals at 39.6 and 34.6 ppm belong to the methylene linkages between phenolic units, the former for a p.p-Ph−CH2−Ph, and the second for an o.p-Ph−CH2−Ph. The peak at 39.6 ppm was higher than the peak at 34.6 ppm for the PUF resin. This is attributed to the superior reactivity of the aromatic hydrogen at the para site of the phenolic −OH rather than that at the ortho site. At the initial stage of the resin synthesis process, a hydroxymethylated reaction took place at the para site of the phenolic −OH within phenol. The following condensation reaction easily took place between the para methylol group and the unreacted para site of the phenolic −OH in the phenol. Therefore, a large proportion of the para sites of the phenolic −OH were consumed to form para−para methylene bonds.10

3.5. CP-MAS 13C NMR of Uncured and Cured Resin Adhesives. The curing behaviors of the PUF and PRUF resin adhesives were explored by analyzing the uncured and cured resin adhesives via solid-state CP-MAS 13C NMR. Figures 5 and 6 display the spectra of the uncured and cured resin adhesives, respectively. The signal assignments of the PUF resin adhesives were similar to the PRUF resin adhesives, despite being uncured or cured. The new spectra signals around 79 ppm are attributed to spinning sidebands. Furthermore, the peak around 61.3 ppm decreased slightly compared with the signals of all resin adhesives before curing. This was caused by the methylene bridges between phenolic ring breaking during the curing process. This implied that the main reaction of the curing process was the condensation reaction between the ortho methylol groups and the remaining unreacted ortho and para sites. In addition, the signals of the formaldehyde around 80–100 ppm were not observed in the spectra of the cured resin adhesives, as shown in Figure 6, which was in agreement with the results shown in Table 3.

4. CONCLUSIONS

The eco-friendly plywood was successfully prepared with these PRUF resin adhesives, based on the proposed formulation. The cost of resorcnil and the performances of the resin adhesives were taken into account in determining that the addition of resorcnil was feasible at a 1.3% (based on resin, w/w) substitution rate. The ortho and para sites of resorcnil reacted completely when they were added at the beginning of the second stage, rather than simply mixing them with the phenolic resins. The thermodynamic studies indicated that the additional resorcnil could reduce the activation energy of resin up to 28.8% more than the PUF resin adhesive without any curing agent. The PRUF resin adhesives exhibited better performances for decreasing the curing temperature and accelerating the curing process of resins. In this study, the plywood prepared with PRUF resin adhesives exhibited low formaldehyde emissions (≤0.1 mg L−1) and acceptably high bonding strengths (>1.00 MPa). The PRUF resin adhesives, therefore, have a great potential use in wood panels prepared with agricultural and forest residues.

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Notes
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