EFFECTS OF ESTERS AND RESORCINOL ON PHENOLIC RESINS AS ADHESIVES IN MEDIUM-DENSITY FIBERBOARD MANUFACTURING

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Abstract. Phenol–formaldehyde (PF) resin-bonded composite wood panels exhibit very low formaldehyde emission levels, meeting the most stringent regulations. However, slow cure speed is a major limiting factor for its applications in the economical manufacturing of medium-density fiberboard (MDF) and particleboard. Commercial PF resins accelerated with esters or resorcinol and their applications in the manufacturing of MDF were investigated in this article. It was found that although ethylene carbonate, propylene carbonate, and triacetin were very effective in reducing the gel time of phenolic resins, these esters caused substantial loss of bonding strength, particularly in the case of phenolic resins with high alkalinity. The loss of bonding strength increased as the ester loading level in the PF resin was increased. On the other hand, resorcinol was not only an effective PF accelerator, but also preserved most of the bonding strength. Resorcinol-accelerated PF adhesives showed better performance in internal bond strength, bending strength, and water resistance of MDF in comparison with the ester-accelerated PF adhesive systems. The cure speed of the resorcinol-accelerated PF adhesive was evaluated against a urea–formaldehyde (E2 type) in the manufacturing of MDF.

Keywords: Phenolic resin, ester, resorcinol, formaldehyde emission, medium-density fiberboard.

INTRODUCTION

Medium-density fiberboard (MDF) and particleboard (PB) panels are usually produced with urea–formaldehyde (UF) adhesives. All UF-bonded products release varying amounts of formaldehyde vapor throughout the manufacturing processes and the entire service life. For the past 25 yr, formaldehyde emissions of MDF and PB products have been very substantially reduced by lowering the formaldehyde/urea molar ratios of UF and melamine–urea–formaldehyde (MUF) resins, the use of formaldehyde scavengers, or the combination of these approaches. Currently, MDF and PB panels produced in North America have formaldehyde emissions typically below 0.21 and 0.18 ppmv, respectively (using the North American large-scale chamber test, ASTM 2002), meeting the CARB phase 1 requirements in California. Most MDF/PB manufacturers in North America are preparing to satisfy the CARB phase 2 requirements (CARB 2007) by January 2011, which set the formaldehyde emission limit for MDF at 0.11 ppmv and PB at 0.09 ppmv. These are similar to the formaldehyde emission limits of the European E1 standard. The Japanese F**** standard (JIS 2003) calls for formaldehyde emissions

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below 0.05 ppmv (also regarded as E0). Oriented strandboard (OSB) and softwood plywood panels manufactured in North America are commonly bonded with phenol–formaldehyde (PF) adhesives and already are meeting the F**** standard. Therefore, there are no consumer issues concerning formaldehyde emissions from OSB and softwood plywood. These ultralow levels of formaldehyde emissions are also where MDF/PB products should be. However, continuing the use and modifications of UF or MUF adhesives would make it difficult to meet the increasingly stringent formaldehyde emission regulations because nitrogen–carbon bonds in these adhesives are inherently vulnerable to hydrolysis, resulting in slow but continuous release of formaldehyde (Myers 1985). Looking at various other kinds of available technologies such as panel posttreatments (Meyer 1983), UF resin modification (Calve and Brunette 1984), furnish treatment (Wu and Wuu 1987), and use of polymeric diphenylmethane diisocyanate (Wang et al 2004), an attractive option is to use PF resins in MDF and PB (as in the cases of OSB and softwood plywood).

Although PF resin costs more than twice that of UF resin, it is much more efficient and has lower consumption. PF resin is the lowest cost commercial wood adhesive after UF resin because it is used in large quantities for OSB and plywood. Cured PF resins are highly resistant to hydrolysis because of the high stability of carbon–carbon bonds, therefore PF-bonded wood composite panels emit very little formaldehyde and are extremely durable when exposed to water. In this way, PF-bonded MDF/PB products can effectively overcome the two most widely known problems of UF-bonded MDF/PB products: high formaldehyde emissions and poor water durability. These improved product attributes could lead to new applications and open new markets if the manufacturing cost of PF-bonded MDF and PB could be reduced to competitive levels through research and development. Whereas PF has shown higher bonding efficiency than UF, its cure speed is slower than that of UF. Slow resin cure rate would lead to lower production rates and higher production costs. This is perhaps the most important reason that PF resins are not used widely for MDF and PB. However, if the cure speed of PF could be increased by a catalyst or accelerator, the economic viability as a MDF/PB adhesive would be improved. It is known that some esters are effective in the acceleration of phenolic resin curing (Pizzi 2003; Kamo et al 2004). This technique is now used extensively for foundry core PF binders (Lemon 1990). Recent research also suggested that ester-accelerated PF resin may have potential in the manufacturing of wood composite panel products (Park et al 1999; Zhao et al 1999).

To find an effective, economical, and user-friendly catalyst (or accelerator) to increase PF resin cure speed and to demonstrate the viability of catalyzed PF in producing MDF with formaldehyde emissions less than 0.05 ppmv, this article examines the effects of ethylene carbonate (EC), propylene carbonate (PC), glyceryl triacetate (GT), and resorcinol (RC) on PF resins as adhesives.

MATERIALS AND METHODS

Chemicals and Wood Fiber

The chemicals and wood fiber used were:

* Cascophen LP02: Liquid PF resin for OSB face layers (55.0% solids)
* Cascophen HPC51: Liquid PF resin for OSB core layer (51.0% solids)
* Casco-resin CP251LS: Liquid UF resin for PB (62.0% solids)
* Cascowax EW-58S: Emulsion wax (58.0% solids)
Ethylene carbonate (solid)
Propylene carbonate (liquid)
Glyceryl triacetin (liquid)
Resorcinol (solid), used as a 40% aqueous solution
Urea (solid), used as a 40% aqueous solution
Sliced aspen veneers for lap shear tests
Eastern Canadian SPF virgin fiber for MDF panel manufacturing

* The manufacturer for these resins and emulsion wax was Hexion Specialty Chemicals.

Resin Gel Time Test

Gel time tests were performed for PF resins LP02 and HPC51 at 0.5, 1.0, 1.5, 2.0, and 3.0% ester. Gel time tests were also performed for PF resin LP02 with 0.5, 1.0, and 1.5% RC. The test procedure was as follows: PF resin was poured into a test tube to a depth of 38 mm. The test tube was placed in boiling water, maintaining the water level above the resin. The resin was stirred with a thermometer and the timer started when the resin temperature reached 93°C. It was stirred for 1 min and then for 3- to 5-min intervals until the resin approached a gel; then it was stirred continuously. The gel time was recorded when a string was formed in lifting the thermometer from the resin. The gel time was the elapsed time from 93°C to gelation.

Lap Shear Test

Lap shear tests were conducted using an automated bond evaluation system. The wood substrate was sliced aspen veneer at 6% moisture content (MC) and 0.81-mm thick. LP02 and HPC51 resins and mixtures with esters and RC were used as wood adhesives, respectively. The strands were cut to 100 × 20 mm and the bonding area was 2×10^{-4} m^2. Resin was coated on one surface of each strand; the total resin loading level of the two strands was about 8 g/m^2. Shear strength was evaluated for 200°C hot-pressing temperature and various pressing times. Twenty replicates were done for each condition.

Medium-Density Fiberboard Panel Manufacturing

Three groups of MDF panels with dimensions of 711 × 711 × 9.5 mm were produced with a target density of 770 kg/m^3. Eastern Canadian spruce–pine–fir virgin fiber with an initial MC of less than 10% was used as the raw material. The conventional 10-mm MDF press strategy was adopted for pressing all panels.

In the first group, the adhesives were PF resin HPC51 with 1.0 and 1.5% EC and LP02 PF resin with 1.5% EC, 1.0% PC, and 2% RC. The accelerator solids percentages were based on liquid resin weights. A calculated amount of 10% ester aqueous solution or 40% RC aqueous solution was premixed with a PF resin immediately before blending with wood fiber. The PF resin loading was 7% on a resin-solids/dry-fiber basis. No wax or formaldehyde scavenger was used. The hot-press temperature was set at 205°C, and press times were 330, 300, 270, and 240 s. One panel was made for each condition.

In the second group, PF resin LP02 with 2% RC and UF resin CP251LS were used as adhesives. The resin solids add-on was 7% for PF and 12% for UF. Emulsion wax solids add-on was 0.5% for both PF- and UF-bonded MDF panels. Urea/water scavenger (40% urea aqueous solution) was used for the UF-bonded panels at a 1.0% urea solids add-on. The press temperature was 205°C for PF-bonded panels and 182°C for UF-bonded panels. Press times were 255, 240, and 225 s. Duplicate panels were produced for each condition.

Panel Property Test

Three-point bending (for modulus of elasticity [MOE], and modulus of rupture [MOR]), internal bond [IB] strength and 24-h water soak tests were conducted for all panels. Four bending specimens (338 × 75 mm), 4 water-soak specimens (152 × 152 mm), and 10 IB specimens (50 × 50 mm) were cut from each panel. The mass and dimensions of specimens were measured for calculating density. All mechanical tests were conducted using an Instron Universal Machine with a loading speed of 5 mm/min.

Formaldehyde Emission Test

Formaldehyde emission tests were conducted for some MDF panels made in the second group. The tests followed the North American small chamber test standard (ASTM 2006).

RESULTS AND DISCUSSION

Gel Times of Ester-Accelerated Phenol–Formaldehyde Resins

LP02 is a PF resin commercially used as an OSB face adhesive. Figure 1 illustrates the gel times of LP02 in the presence of various amounts of esters and RC. The PF resin gel time can be very dramatically reduced by either esters or RC. However, the relationship between the gel time and ester content was nonlinear. EC and PC showed similar effects on the reduction of PF gel time and the effects were more pronounced at lower EC or PC additions. The effects of GT and RC were less dramatic but still substantial.

HPC51 is a PF resin commercially used as an OSB core adhesive. It has a higher alkalinity than that of LP02 resin. The effects of various amounts of EC (used as a 16% aqueous solution), PC, and GT on gel time of HPC51 are shown in Fig 2. The trends of these esters appeared to be similar. The effect of gel time reduction of GT was more pronounced in HPC51 than in LP02. This was probably because of the higher alkalinity of HPC51. As shown in Fig 3, gel time reduction with ester is pH-dependent. The GT-accelerated gel time of LP02 resin showed more dramatic reduction at higher pH when the pH of LP02 (pH = 10.6) was adjusted to the same as that of HPC51 (pH = 12.2) with a 50% sodium hydroxide solution. It was also noted that the reactivity of EC was higher than that of PC in LP02, whereas the reactivity of EC was lower than that of PC in HPC51. This was probably because of the use of EC as a dilute water solution (16%) in HPC51. Water diluted the resin mixture and hence delayed the gel time (Fig 4).

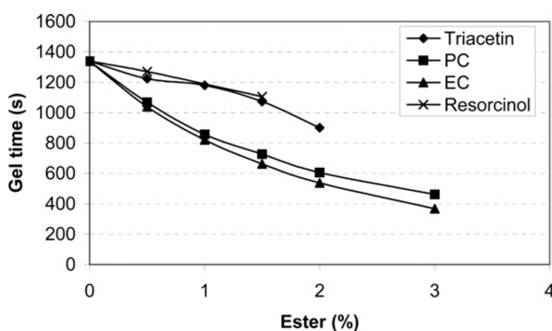

Figure 1. Effects of esters and resorcinol on gel times of phenol–formaldehyde resin LP02.

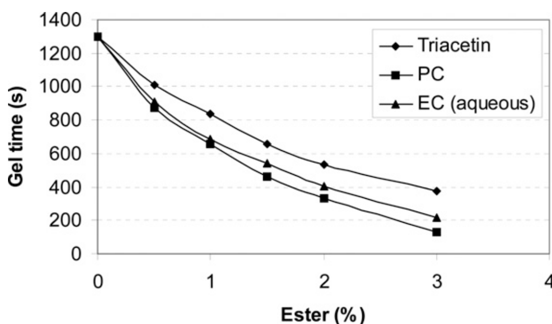

Figure 2. Effects of esters on gel times of phenol–formaldehyde resin HPC51.

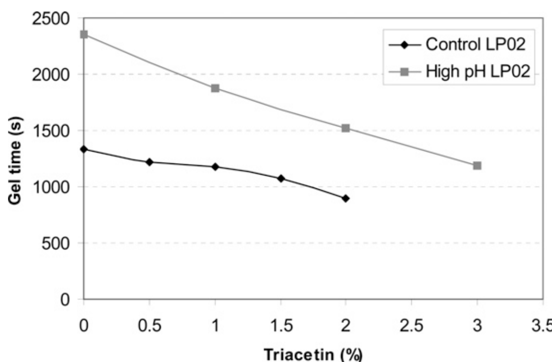

Figure 3. Effect of pH on triacetin-accelerated gel times of phenol–formaldehyde resin LP02.

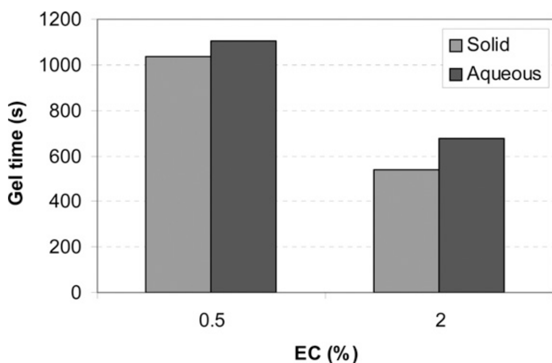

Figure 4. Effect of ethylene carbonate (EC) (solid and aqueous) on gel times of LP02 resin.

Bonding Strength in Lap Shear Tests

The bonding strength of HPC51 PF resin with and without the addition of 1% EC was carefully evaluated using the lap shear tests of aspen strands at 200°C press temperature and various press times (30, 60, 90, 120, and 180 s). The results of these tests are shown in Fig 5. Looking at the control (resin without EC), the maximum shear strength was reached at 90-s press time. However, for resin with EC, the maximum shear strength was reached at 60-s press time. These data indicated that the ester did accelerate the PF resin curing. Unfortunately, bonding strength decreased in all cases with ester.

Figure 6 further illustrates that both EC and PC decreased the lap shear strength for LP02 and HPC51 resins. Clearly, the bonding strength also decreased with increasing ester contents. Notably, RC showed less decrease of lap shear strength than the esters. Considering that esters and RC can shorten PF resin gel time dramatically but also cause bonding strength reduction, the benefits of shorter press cycles of panel production can be realized only if the reduced bonding strength is adequate to hold the panel together and prevent steam blows at shorter press times. Therefore, a successful PF accelerator will be the one that can shorten PF cure time, thereby causing only minimum reduction of bonding strength. It is believed that faster resin curing may result in more resin precuring and/or induce more defects in the resin molecule crosslinking network after curing, both of which can reduce the bonding strength of wood with PF resin.

It is noteworthy that LP02 (an OSB face resin) produced better bonding strength than HPC51 (an OSB core resin) with or without ester. This is perhaps because of the higher alkalinity in HPC51 resin and/or a higher urea content in HPC51.

Medium-Density Fiberboard Panel Manufacturing and Testing

Effects of ethylene carbonate, propylene carbonate, and resorcinol on phenol–formaldehyde-bonded medium-density fiberboard. Five experiments were conducted to evaluate the effects of EC, PC, and RC on press speed and panel properties of PF-bonded MDF. The PF resin loading was 7% throughout these experiments (resin solids percentage on a dry wood fiber basis). No wax was applied. HPC51 (a commercial OSB core resin) and LP02 (a commercial OSB face resin) phenolic resins were used and evaluated separately.

In Experiment 1, HPC51 with 1% EC was used as an adhesive. In Experiment 2, EC loading in HPC51 was increased to 1.5%. Therefore, the effects of different application rates of EC can

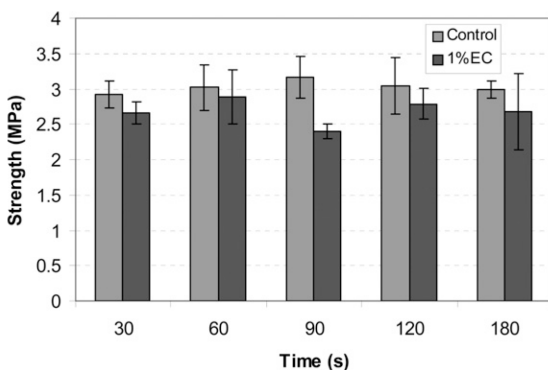

Figure 5. Lap shear strengths of HPC51 phenol–formaldehyde resin with and without 1% ethylene carbonate at different press times.

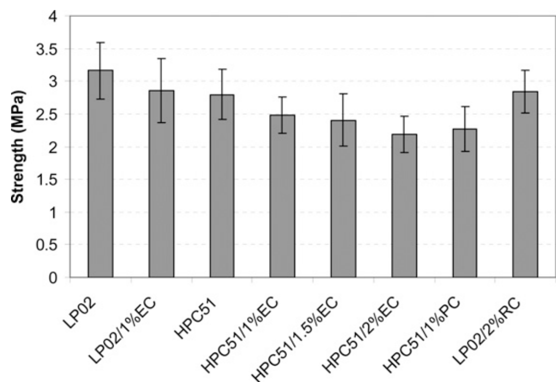

Figure 6. Lap shear strength of LP02 and HPC51 phenol–formaldehyde resins with different concentrations of accelerators.

be seen by comparing the panel test results of these two experiments. In Experiment 3, EC loading was kept at 1.5%, but the resin was changed to LP02. By comparing the panel test results of Experiments 2 and 3, the effects of EC on different PF resin systems can be observed. In Experiments 4 and 5, the adhesive systems were changed to 1% PC in LP02 and 2% RC in LP02, respectively. The effects and differences of these accelerators can then be observed. The average test results of the MDF panels, which were produced with the previously mentioned accelerated phenolic resin systems at 205°C press temperature and different press times, are summarized in Table 1.

Comparing the panels bonded with HPC51 PF resin and 1% EC (panels 1-EC-1 to 1-EC-4) with the panels bonded with HPC51 and 1.5% EC (panels 2-EC-1 to 2-EC-4), the same phenolic resin and board-manufacturing conditions were applied but board performance decreased as the ester loading increased (see Table 1). Although IB appeared to reach the maximum at shorter press time when higher ester loading was used, IB strength and bending strength were lower and water resistance decreased. These findings are consistent with those results obtained from the gel time and lap shear tests.

Comparing the panels bonded with HPC51 PF resin and 1.5% EC (panels 2-EC-1 to 1-EC-4) with the panels bonded with LP02 PF resin and 1.5% EC (panels 3-EC-1 to 3-EC-4), the same panel manufacturing conditions and ester loading were applied, but LP02 resin appeared to produce better IB strength and water resistance than those of HPC51 resin, although the IB appeared to reach a maximum at shorter press times with HPC51. This finding is again consistent with the results obtained from the lap shear and gel time tests (see Table 1 and Figs 1, 2, and 6). Therefore, a low-alkalinity PF resin (resol type) is more desirable when a PF accelerator is used.

Table 1. Average results of medium-density fiberboard bonded with accelerated phenol–formaldehyde (PF) adhesive systems.

Panel ID[a]	PF/accelerator	Accelerator (%)	Press time(s)	Density (kg/m^3)	IB (MPa)	MOE (GPa)	MOR (MPa)	WA (%)	TS (edge) (%)
1-EC-1	HPC51/EC	1.0	330	800 (20)[b]	0.59 (0.08)	3.1 (0.3)	28.2 (2.5)	90.7 (17.1)	29.5 (2.5)
1-EC-2		1.0	300	790 (10)	0.61 (0.06)	3.0 (0.1)	30.4 (1.9)	97.4 (12.5)	30.0 (2.3)
1-EC-3		1.0	270	770 (10)	0.50 (0.07)	2.9 (0.0)	27.6 (0.9)	83.9 (10.4)	27.4 (2.6)
1-EC-4		1.0	240	770 (10)	0.44 (0.08)	2.9 (0.1)	25.0 (1.1)	93.4 (8.9)	32.4 (2.4)
2-EC-1	HPC51/EC	1.5	330	780 (20)	0.39 (0.06)	2.8 (0.2)	22.0 (2.1)	111.2 (4.6)	41.2 (1.2)
2-EC-2		1.5	300	780 (20)	0.43 (0.05)	2.9 (0.1)	24.1 (1.7)	115.9 (9.7)	40.0 (1.6)
2-EC-3		1.5	270	760 (20)	0.44 (0.05)	2.9 (0.2)	25.0 (2.6)	108.5 (5.9)	37.6 (1.3)
2-EC-4		1.5	240	800 (20)	0.37 (0.06)	3.0 (0.1)	24.4 (0.9)	109.1 (7.7)	41.3 (3.2)
3-EC-1	LP02/EC	1.5	330	780 (10)	0.59 (0.11)	2.6 (0.1)	23.1 (2.2)	106.7 (3.8)	30.9 (1.5)
3-EC-2		1.5	300	760 (30)	0.48 (0.11)	2.6 (0.2)	22.6 (1.4)	88.7 (6.1)	28.5 (0.7)
3-EC-3		1.5	270	760 (40)	0.52 (0.13)	2.8 (0.1)	25.7 (1.8)	92.8 (11.4)	29.6 (0.7)
3-EC-4		1.5	240	770 (20)	0.51 (0.08)	2.7 (0.3)	24.6 (3.6)	92.9 (15.5)	30.3 (2.6)
4-PC-1	LP02/PC	1.0	330	810 (20)	0.53 (0.14)	2.7 (0.1)	28.6 (2.9)	92.7 (5.4)	25.8 (0.1)
4-PC-2		1.0	300	810 (30)	0.67 (0.16)	3.1 (0.2)	29.1 (3.9)	92.7 (6.3)	26.3 (0.4)
4-PC-3		1.0	270	830 (50)	0.58 (0.20)	3.1 (0.4)	30.4 (4.4)	94.8 (5.7)	23.9 (0.7)
4-PC-4		1.0	240	800 (30)	0.47 (0.10)	2.9 (0.2)	28.9 (2.1)	89.5 (4.0)	25.5 (0.6)
5-RC-1	LP02/RC	2.0	330	800 (40)	0.85 (0.20)	3.1 (0.1)	34.2 (2.8)	99.1 (4.2)	24.1 (0.6)
5-RC-2		2.0	300	740 (40)	0.70 (0.11)	2.6 (0.1)	28.3 (1.7)	94.7 (3.9)	25.1 (0.9)
5-RC-3		2.0	270	780 (30)	0.73 (0.12)	3.1 (0.3)	33.0 (4.2)	101.5 (4.2)	25.8 (0.3)
5-RC-4		2.0	240	790 (40)	0.72 (0.12)	2.9 (0.1)	30.2 (1.8)	99.3 (2.3)	27.0 (6.2)

[a] Panels obtained from Experiments 1, 2, 3, 4, and 5 are identified by the first number of the panel ID.
[b] Standard deviation.
IB, internal bond; MOE, modulus of elasticity; MOR, modulus of rupture; WA, water absorption; TS, thickness swelling.

Comparing the panels bonded with HPC51 PF resin and 1% EC (panels 1-EC-1 to 1-EC-4) with the panels bonded with LP02 and 1% PC (panels 4-PC-1 – 4-PC-4), both reached the maximum IB strength at 300-s press time, but the LP02/PC adhesive system appeared to produce somewhat better IB strength and bending strength, although the differences may not be very significant. However, LP02/PC gave significantly better thickness swell.

It is also noted that IB and MOR decreased in 3 of 4 cases of ester applications (see the first 4 groups of panels in Table 1) when extended press time was used (330 s). This may indicate that the cured phenolic resin in the presence of an ester may not be as thermally stable as the cured phenolic resin without. Perhaps an ester can introduce some defects into the crosslinking network of a phenolic resin.

Comparing the panels bonded with LP02 and 2% RC (panels 5-RC-1 – 5-RC-4) to the panels that were bonded with PF/ester adhesive systems, the PF/RC adhesive system performed decisively better in terms of IB strength. It also produced good bending strength and water resistance. Its panel performance had already approached the optimal at the short press time (240 s) and did not deteriorate but somewhat improved at extended press time (330 s). Figure 7 illustrates clearly superior IB strength was achieved by the RC-accelerated PF adhesive system at all press times. Although RC showed the least reduction on phenolic resin gel time among these PF accelerators (see Fig 1), it preserved bonding strength best (see Fig 6). This is probably why RC produced the best results as a PF accelerator. Therefore, resin gel time is not a reliable indicator for the effectiveness of a resin catalyst or accelerator. Bonding strength should also be taken into consideration. Combining gel time with lap shear tests appears to be a much more reliable approach to evaluate resin catalysts or accelerators.

For the comparisons of MOE, MOR, thickness swell (TS), and water absorption (WA) of the MDF panels, see Figs 8, 9, 10, and 11. Lower ester loading rates appeared to give better MOE and MOR than higher ester contents. RC still compared favorably to esters in terms of MOE, MOR, and TS. It is noted that WA was generally high for all panels. This was because no wax was used during the production. Sodium hydroxide in the phenolic resins could also attract more water into the panels.

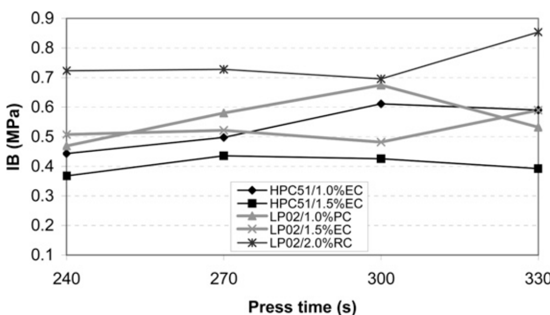

Figure 7. Effects of phenol–formaldehyde resin accelerators on internal bond of medium-density fiberboard panels.

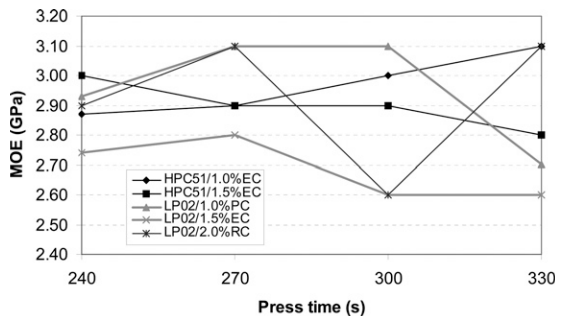

Figure 8. Effects of phenol–formaldehyde resin accelerators on modulus of elasticity of medium-density fiberboard panels.

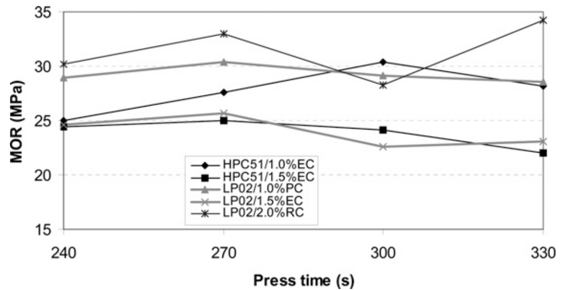

Figure 9. Effects of phenol–formaldehyde resin accelerators on modulus of rupture of medium-density fiberboard panels.

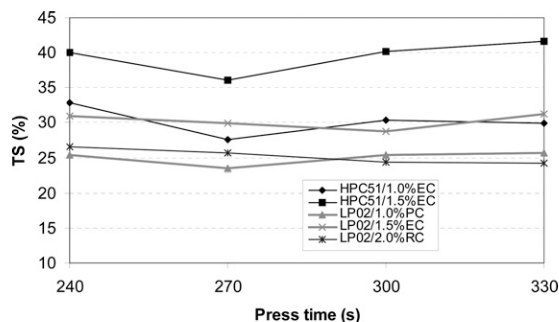

Figure 10. Effects of phenol–formaldehyde resin accelerators on thickness swell of medium-density fiberboard panels.

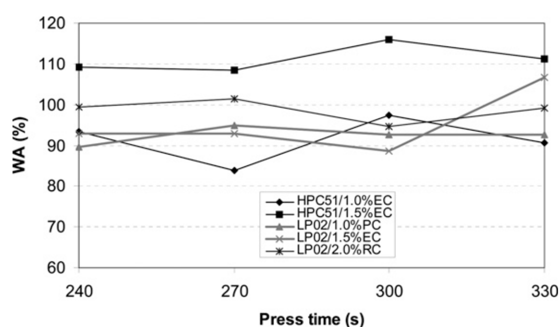

Figure 11. Effects of phenol–formaldehyde resin accelerators on water absorption of medium-density fiberboard panels.

Comparison of phenol–formaldehyde-bonded medium-density fiberboard with urea–formaldehyde-bonded medium-density fiberboard. After determining that RC was the PF accelerator of choice, it was necessary to compare cure speeds and MDF properties for PF and UF resins. Therefore, an MDF experiment was conducted to produce 10-mm-thick MDF panels at different press times with a RC-accelerated PF resin (LP02 with 2% RC) and a UF resin (CP251LS). The UF resin was not catalyzed in this experiment because MDF mills in Canada do not usually use a catalyst. The PF resin loading was 7% and the UF 12% (resin solids on a dry fiber basis). Wax add-on was 0.5% for both panels. Urea water scavenger was used for the UF-bonded boards at a 1% urea solids add-on rate.

The average test results are summarized in Table 2. Despite the fact that the PF resin loading was only about 58% of the UF resin loading, the RC-accelerated phenolic resin produced almost twice the IB strength at the short press time (225 s) as that of UF resin. At extended press times (240 and 255 s), the RC-accelerated phenolic resin produced about 70-80% higher IB strength than that of UF. These conclusions have already taken the panel density differences into consideration (see IB/density column in Table 2). Clearly, PF resin was shown to be a much more efficient adhesive than UF resin. These data also suggested that the cure speed of this RC-accelerated phenolic resin at 205°C press temperature was comparable to that of a UF resin of E2 type at 182°C.

The PF-bonded MDF panels also showed somewhat higher bending strength than the UF-bonded panels (see the MOR and MOE columns in Table 2). Therefore, PF seemed to be able to produce better MDF mechanical properties than UF. Because PF has been widely known for its superior durability in water, the panels were not tested for durability in boiling water. In the 24-h water soak test (at 21°C), however, the PF-bonded MDF and the UF-bonded MDF had similar thickness swells. The PF-bonded panels showed significantly higher water absorption at the short press time (225 s).

The panels derived from the short press time (225 s) were tested for formaldehyde emissions using the small chamber method (ASTM 2006). As expected, the PF-bonded MDF did not have any formaldehyde emissions within the detection limit of this test method, whereas the UF-bonded MDF showed 0.11-0.18 (average 0.15) ppmv.

Overall, this experiment demonstrated that the cure speed of a PF resin can be accelerated with 2% RC to the extent that it is comparable with the cure speed of an uncatalyzed UF resin (E2 type) when conventional press temperatures were used. The experiment also revealed that there is potential to reduce PF resin consumption to one-half of the normal UF resin consumption in MDF manufacturing and still maintain desirable mechanical properties. Therefore, the cost of using PF adhesive to produce MDF should be

Table 2. Average results of medium-density fiberboard bonded with urea–formaldehyde and resorcinol-accelerated phenol–formaldehyde resin.

Panel type	Press time (s)	Density (kg/m^3)	IB (MPa)	IB/density	MOR (MPa)	MOE (GPa)	WA (%)	TS (edge) (%)	HCHO (ppmv)
UF	255	780 (30)[a]	0.41 (0.07)	0.53	28.4 (4.4)	2.9 (0.2)	46.0 (9.8)	18.9 (2.5)	
UF	240	760 (30)	0.40 (0.09)	0.53	31.7 (2.8)	3.1 (0.3)	43.1 (7.3)	19.0 (1.9)	
UF	225	770 (30)	0.43 (0.07)	0.56	31.0 (1.6)	3.0 (0.1)	34.9 (3.2)	15.1 (1.2)	0.15
PF	255	830 (30)	0.73 (0.16)	0.88	32.9 (4.1)	3.3 (0.21)	44.6 (11.6)	16.7 (4.3)	
PF	240	820 (50)	0.75 (0.17)	0.91	35.9 (8.6)	3.3 (0.7)	49.5 (17.0)	18.0 (4.5)	
PF	225	810 (30)	0.84 (0.14)	1.04	33.9 (2.6)	3.1 (0.2)	46.1 (10.1)	17.1 (2.9)	nd[b]

[a] Standard deviation.
[b] Not detectable.
IB, internal bond; MOE, modulus of elasticity; MOR, modulus of rupture; WA, water absorption; TS, thickness swelling.

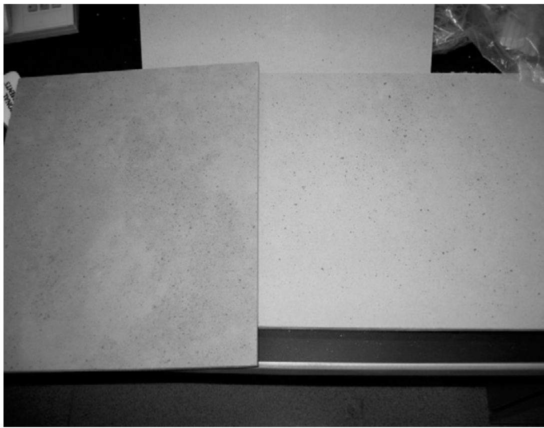

Figure 12. Phenol–formaldehyde-bonded medium-density fiberboard panel (left) showed darker color than urea–formaldehyde-bonded board (right).

substantially lower than previously thought. The added benefits are: 1) extremely low formaldehyde emission from the panel products, easily meeting the toughest formaldehyde standard such as the Japanese F**** standard (<0.05 ppmv or so-called E0); and 2) superior panel durability in water, making the PF-bonded MDF products suitable for both interior and exterior applications. These advantages effectively solve the two commonly known problems associated with current UF-bonded MDF products, ie high formaldehyde emissions and poor water durability. However, the disadvantages of using PF adhesive are darker color on the panel surface (see Fig 12) and higher water absorption. Given that PF resin cost is sensitive to volatile oil prices, the economic viability of using PF adhesive for MDF production should be carefully evaluated. Nonetheless, the findings from this work have provided the basis for a more optimistic view on the economic viability of PF-bonded MDF.

CONCLUSIONS

Based on the experimental data and observations, the authors present the following conclusions:

1. MDF products with ultralow formaldehyde emissions (<0.05 ppmv) can be produced with a PF adhesive. These products can easily meet the most stringent formaldehyde emission standards for wood composite panel products such as the Japanese F**** standard (or E0). The products also have excellent durability in water, being suitable for both interior and exterior applications. The disadvantages of using PF adhesives are darker color on the panel surface and higher WA.
2. Phenol–formaldehyde resin is a far more efficient wood adhesive than UF resin. Using PF at only slightly more than one-half of the UF loading, PF-bonded MDF showed better mechanical properties and about the same TS after 24-h water soak.
3. The cure speed of PF resin can be improved with the use of resorcinol as an accelerator. At 205°C (normal OSB press temperature) and a resorcinol loading of 2% of liquid PF resin weight, a commercial OSB face phenolic resin

used for MDF manufacturing showed comparable cure speed to that of an uncatalyzed commercial UF resin of E2 type at 182°C (normal MDF press temperature in a multi-opening press).

4. Ethylene carbonate, PC, and triacetin are effective PF accelerators, but these esters cause substantial loss of bonding strength, particularly in the case of PF resin with higher alkalinity. They are not recommended for the manufacture of PF-bonded MDF and PB. Conversely, resorcinol is not only an effective PF accelerator, but also preserves most of the bonding strength.
5. Ethylene carbonate, PC, and triacetin are very effective in reducing PF resin gel times. The gel time reduction is pH-dependent with higher pH leading to shorter gel time.
6. Combining gel time and lap shear tests is a far more reliable approach to evaluate and predict PF adhesive (and conceivably UF adhesive) cure speed in wood composite panel manufacturing than using the gel time test alone.

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