Effects of Recycled Fiber Addition on High-Density Fiberboard for Laminated Flooring Bonded with Phenol-Formaldehyde Resin Adhesive

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ABSTRACT: The effects of old corrugated cardboard (OCC) fiber addition on high-density fiberboard (HDF) were investigated in this study. A phenol-formaldehyde (PF) resin was synthesized in the laboratory with resin solids at 50% content as an HDF binder. The physical characteristics and molecular weight of the PF resin are described herein. The laboratory HDFs were made using the OCC fiber based on 0, 20, 40, and 60% oven-dry weight addition with the laboratory-synthesized PF resin. The HDFs were tested for physical strength and dimensional stability properties according to the procedure of ASTM D 1037-99. Evaluation of the HDFs manufactured using the PF resin showed that the internal bond and bending strength properties were decreased gradually with increasing OCC fiber content. Overall, the OCC fiber can be used at a content of 40% in the substitution of raw materials for HDF manufacture. © 2009 Wiley Periodicals, Inc. J Appl Polym Sci 115: 641–645, 2010

Key words: high-density fiberboard; old corrugated cardboard fiber; phenol-formaldehyde resin; recycled fiber

INTRODUCTION

In 2005, according to the United States Environmental Protection Agency, 245 million tons of municipal solid waste (MSW) was generated in the United States, equating to ~ 4.5 pounds of waste per person per day.[1] It was estimated that 53% of the MSW stream consisted of paper and paperboard (34.2%), yard trimming (13.1%), and wood (5.7%). These materials, which are wood-based resources and other lignocellulosic materials, provide a potential resource for the additional recovery of wood or wood fiber for commercial uses.

Since fiberboard-substrate laminate flooring was invented by the Swedish company Pergo in 1980, it was introduced to the European flooring market in 1984 and the North American flooring market in 1994.[2] Laminate flooring, which is produced in board form, is made up of a core layer of high-density fiberboard (HDF) and a face layer of a decorative paper, (typically wood grain pattern) impregnated with melamine resin under high temperature and pressure.[3] Laminate flooring has been widely used in residential and commercial buildings.[4]

In 2005, the global consumption of laminate flooring was 815 million m^2.[5] In Europe, the consumption of laminate flooring was 528 million m^2, accounting for 65% of the total laminate flooring consumed worldwide. The Asian and North American market shares for the consumption of the total laminating flooring were 26% and 8%, respectively.[5]

The phenol-formaldehyde (PF) resin adhesive consumption in 2000 in North America was 1233 kt.[6] PF resin is traditionally used as the binder of wood composite products such as plywood, wood flooring board, oriented strandboard, and fiberboard, due to its excellent durability and water resistance.

The objective of this study was to determine the effects of old corrugated cardboard (OCC) fiber addition on the properties of HDF bonded with the laboratory-synthesized PF resin adhesive. A PF resin was formulated for bonding HDF using the OCC fiber as a partial virgin fiber replacement to improve the panel's properties. The HDF's properties were compared with those of panels bonded with the OCC fiber addition.

MATERIALS AND METHODS

PF resin synthesis

PF resin was formulated in the laboratory with sodium hydroxide contents of 2.94% over total liquid resin weight and formaldehyde/phenol (F/P) mole ratios of 2.1.

The PF resin formulation procedure synthesized in this study is summarized in Table I. Sodium hydroxide (50% solution) and phenol were charged into a stirred reactor and the reaction mixture was heated

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TABLE I
Phenol-Formaldehyde Resin Formulations Synthesized in This Study

Step	Material	Wet weight (g)	Dry weight (g)	Time (min)	Temperature (°C)	Procedure and observation
A	NaOH (50%)	194.0	97	0	25	Charge and heat
B	Phenol (90%)	1181.9	1063.7	1	45	Charge, heat, and agitate
C				20	65	Heat to 65°C
D	HCHO (37%)	1924.6	712.1	25	70	Add HCHO dropwise
				65	70	Complete HCHO addition
E				75		Increase temperature to 85°C
F				105	85	At 85°C, maintain agitation and hold for a G-H viscosity of "F"
					85	
G				170	85	Start cooling
					25	Storage
Total		3300	1872.8			

G-H viscosity, Gardener-Holdt viscosity.

to 65–70°C. Formaldehyde solution (37% conc.) was then added dropwise over a period of 40 min while the reaction temperature was held constant in the same range by intermittent cooling using an ice bath. After the formaldehyde addition was completed, the reaction temperature was maintained at the same range for about 10 min and then was gradually increased to 85°C over a period of 30 min. This reaction temperature was maintained until the resin attained a viscosity on the Gardener-Holdt viscosity scale of "F." The resin was cooled directly to room temperature at this viscosity point and stored frozen until property analysis and use.

PF resin analysis

The viscosity of the laboratory-synthesized PF resin was measured with a Brookfield Viscometer (Stoughton, MA), model RVF, spindle number 1 at 2.09 rad/s (20 rpm) rotation. After pH meter (Mettler-Toledo, Beaumont Leys, Leicester, England) was calibrated with standardized buffer solutions at pH 7.0 and 10, the pH was measured at 25°C. Gel time was measured using a Sunshine gel timer (Philadelphia, PA) at 100°C. Free formaldehyde content was measured by the hydroxylamine hydrochloride method.[7] Molecular weight was determined by a gel filtration chromatographic method using 0.10*N* sodium hydroxide solution as eluant, Sephacryl 400 gel, and a UV detector set at 280 nm. Since the molecular weight calibration of this analysis was made by using available linear polystyrene sulfonate molecular weight standards, the obtained molecular weights are only relative measures because of the branched polymer chains.[8]

Fiber preparation

The virgin fiber of *Pinus densiflora* Siebol et Zuccarini and the OCC fiber were the raw materials for this study. The virgin fiber and the OCC fiber were supplied by a commercial medium-density fiberboard plant in Korea. Defibrator was used for refining wood chips under conditions considered best. The OCC fiber was produced with a defibrator at atmospheric conditions. The refining condition of OCC fiber is proprietary. After refining, all wood fibers were dried to a moisture content of about 4% in a dryer before use. The size classification of the fibers was performed according to Technical Association of the Pulp and Paper Industry (Tappi) standard T 233 cm-95.[9]

HDF manufacture

HDF panels were made using four different ratios of OCC fiber content. The percentages of OCC fiber addition were 0, 20, 40, and 60% by oven-dry weight of the total fiber for the panels. To obtain a better mixture of both virgin and OCC fibers, the two types of fibers were hand-mixed and blended with the laboratory-synthesized PF resin in a rotary drum blender. The liquid PF resin applied with an air spray system at 172 kPa (25 psi) pressure. Using the mixture, a mat was formed in a laboratory air-forming system (Fig. 1). The fibers were forced by brushing through the 6-mm screen on the top of the forming box. This allowed individual fibers and fiber bundles to pass through and collect at the bottom of the forming box. HDFs were then manufactured using the processing parameters reported in Table II.

HDF performance test

Test specimens were cut from boards (Fig. 2). Internal bond (IB), modulus of elasticity (MOE), and modulus of rupture (MOR) values were determined in accordance with the ASTM procedure D 1037-99.[10] Panel water absorption and thickness swelling properties were observed after 2- and 24-h soaking tests.

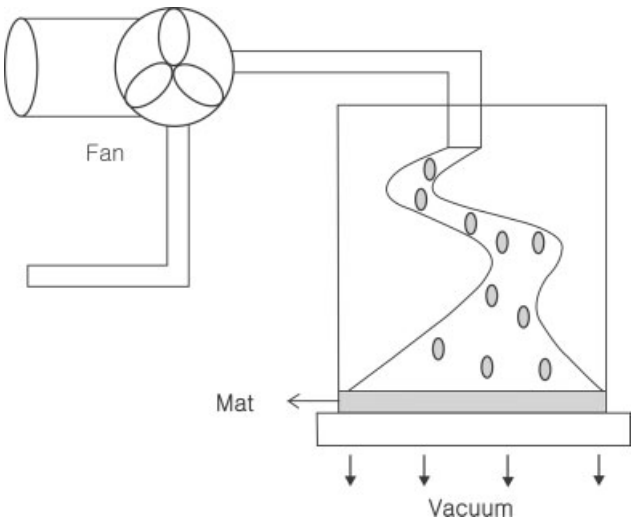

Figure 1 Air-forming system for laboratory HDF manufacture.

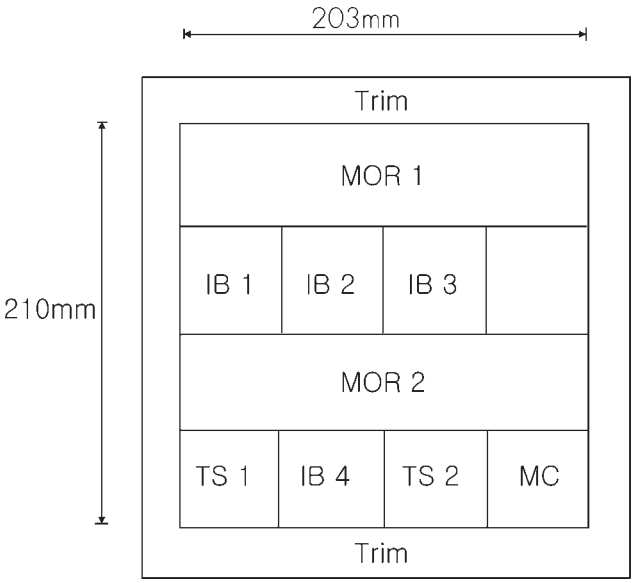

Figure 2 Cutting diagram of laboratory HDFs for sample property testing.

Statistical analysis

Panel property test results were analyzed using the Statistical Analysis System (SAS) programming package.[11] The analysis of variance (ANOVA) was used to determine differences within each panel type. Significant differences (0.05 level) were further compared by the *t* test for least significance differences (LSDs) from the SAS program.[12]

RESULTS AND DISCUSSION

PF resin properties

The resin viscosity was 218 mPa s, which was suitable for resin spray application (Table III). The resin made in this study showed very low free formaldehyde contents (0.05%), as expected. The resin had a pH of 9.9, gel time of 31.4 min (at 100°C), and weight average molecular weight of 2290. Generally, the molecular weight of the resin was closely related with the panel's bond strength.[13]

TABLE II
Panel Manufacturing Parameters

Panel dimensions	250 mm × 250 mm × 6.3 mm
Mat moisture content	8–9%
Wax and resin solids loading	1 and 8%, respectively, based on oven-dry wood weight
Target board density	900 kg/m^3 objective
Catalyst	None
Resin flow rate	130 mL/min
Hot press temperature	180°C
Hot press times	4 min
Replication	Five boards per condition (total of 20 boards)

Fiber size classification

The coarse fraction retained on the 1.19-mm mesh screen opening was higher for virgin fiber (28%) than for OCC fiber (19%) (Table IV). The fine fraction passing a 0.149-mm mesh screen opening was lower for virgin fiber (15%) than for OCC fiber (28%). The amount retained on intermediate screens was about equal for both types of fibers. This result shows that the fine fraction of OCC fiber has more than virgin fiber. The conditions in the defibrator can affect properties of HDF made with OCC. The fiber size distribution is important for the performance of panel.

HDF performance test

The HDF densities in this study ranged from 854 to 901 kg/m^3 (Table V); panel density decreased with

TABLE III
Physical Properties of PF Resin Synthesized in This Study

Property	Unit	PF resin
pH	–	9.9
Gel time (at 100°C)	min	31.4
Alkalinity (titration)	%	2.7
Viscosity	mPa s	218
Free formaldehyde	%	0.05
Molecular weight characteristics	Daltons	
M_w		2290
M_n		840
M_w/M_n polydispersity		2.73

M_w = weight-average molecular weight; M_n = number-average molecular weight.

TABLE IV
Fiber Size Classification Produced from Fiber Type in This Study

Fiber type	Mesh screen openings (mm)				
	+1.19	−1.19/+0.595	−0.595/+0.297	−0.297/+0.149	−0.149
Virgin fiber	28	24	16	17	15
OCC fiber	19	16	17	20	28

Plus indicates percentages of fibers retained on mesh screen opening; minus indicates percentages of fibers passed through mesh screen opening.

increasing OCC fiber content. However, the LSD test showed that the panel density was not significantly affected by the OCC fiber addition.

The IB range for all panels was 0.66–2.0 N/mm^2 (Table V) In general, the IB value decreased with increasing OCC fiber content, although the panels with an OCC fiber content of 20 and 40% had equivalent IB. The LSD test showed that IB was significantly affected by OCC fiber contents. This decreasing trend of IB with increasing OCC fiber might indicate that OCC fiber needs more resin loading to obtain the same IB as polar virgin fiber. The larger total fiber surface area caused by adding the smaller OCC fiber needs more resin to maintain IB. Previous research reported that increasing resin loading generally improved the panel's physical and mechanical properties.[14]

The MOE range for all panels was 1985–3933 N/mm^2 (Table V). The LSD test for MOE showed no significant variation from the control panel for the panels with 20 and 40% OCC fiber content but a significant variation for the 60% OCC fiber content panel.

The MOR range for all panels was 19.3–45.0 N/mm^2 (Table V). The LSD test for MOR showed that the control panel did not differ significantly from the panels made with 20 and 40% OCC fiber content but did differ from 60% OCC fiber content panel. The relatively large amount of smaller OCC fiber length and total fiber surface area affected negatively bending properties such as MOE and MOR.

The thickness swell range for all panels was between 4.1 and 5.5% for the 2-h test and between 15.0 and 19.5% for the 24-h test (Table V). The LSD test for thickness swell after 24-h water soaking showed that the control panel had a significantly lower thickness swell value than the panels with 40 and 60% OCC fiber content, whereas the control panel and that with 20% OCC fiber content had equivalent thickness swell. This difference was probably related to the OCC fiber's greater hydrophilic property, because the OCC fiber has a relatively lower lignin content than does the virgin fiber.

The water absorption range for all panels was between 9.8 and 14.2% for the 2-h test and between 39 and 52.0% for the 24-h test (Table V). The LSD test for water absorption after 24-h water soaking showed that the control panel absorbed significantly lower amounts of water than the panel with 60% OCC fiber content. However, the 24-h water absorption of the panel with 20% OCC fiber content was comparable to that of the panel with 40% OCC fiber content. It was observed that the longer fiber length or the less total fiber surface area, the less the thickness swell and water absorption of the panel.

CONCLUSIONS

OCC fiber was used as a raw material for the manufacture of HDF. Performance test evaluation showed that the HDF's mechanical properties decreased gradually with increasing OCC fiber content over the range of 0–60%. Although the physical and mechanical properties differed significantly according to OCC fiber content, the raw material content which exhibited the best overall properties for HDF manufacture according to the result of this research was 40%. All panels with 60% OCC fiber content

TABLE V
Performance Test Results of HDFs Made from Recycled Fiber

Recycled fiber addition (%)	Panel density (kg/m^3)	IB	MOE (N/mm^2)	MOR (N/mm^2)	Thickness swell (%)		Water absorption (%)	
					2 h	24 h	2 h	24 h
0	901 (0.9)^a	2.0 (3.1)^a	3933 (10.9)^a	45.0 (9.2)^a	4.1 (5.3)^c	15.0 (6.9)^c	9.8 (6.4)^{bc}	39 (3.0)^b
20	863 (1.5)^a	1.28 (6.8)^b	2983 (10.4)^{ab}	30.0 (11.2)^{ab}	4.7 (10.0)^{bc}	16.5 (9.7)^{bc}	11.6 (2.9)^{ab}	45.5 (5.8)^{ab}
40	874 (2.2)^a	1.09 (7.2)^b	2886 (8.8)^{ab}	27.0 (11.7)^{ab}	5.0 (11.6)^{ab}	17.5 (8.1)^b	12.4 (7.8)^{ab}	47.0 (4.5)^{ab}
60	854 (3.1)^a	0.66 (8.6)^c	1985 (14.8)^b	19.3 (11.7)^b	5.5 (10.4)^a	19.5 (12.8)^a	14.2 (3.8)^a	52.0 (7.1)^a

Values in parentheses are coefficients of variations. Means with the same superscript letter are not significantly different (0.05 level).

did not meet the minimum strength requirements for HDF of the Korean Standard KS F 3200 fiberboards.

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