
Composite from Wood Fibres Bonded with Renewable Wood Resin

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SUMMARY

This paper shows the efficiency of a renewable wood resin as a binder for wood fibres in the manufacture of environmentally friendly fibreboard composites. The wood resin was nevertheless partially replaced by urea formaldehyde (UF) resin to make fibreboards more economical and performance-driven. The results demonstrate that nearly all the mechanical properties of the fibreboards were above the minimum requirements specified in the ANSI-AHA standard.

The mechanical properties of wood resin bonded fibreboard were inferior to those of the UF resin bonded equivalents. The horizontal density profiles of the composites revealed that the wood resin distribution in the wood fibres could be optimised in presence of liquid UF resin. Wood resin bonded fibreboard showed a lower rate of formaldehyde emission than UF resin bonded fibreboard. The curing conditions were also optimised to achieve improved mechanical performance and dimensional stability for the composite fibreboards.

INTRODUCTION

There is impetus in research related to the development of composite fibreboards from renewable wood and agricultural resources to replace petroleum based composites for economic and environmental reasons. These composite fibreboards are used as non-structural materials for building construction, furniture, cabinets and storage, appliances, automotive and rolling stock. The wood industries are interested in the manufacture of fibreboard composite from wood fibres because of their low specific gravity, high specific strength and low processing costs^{1,2}.

The porous structure and active surface of wood fibres can produce excellent bonding with several thermoset or thermoplastic resins. Sain *et al.*³⁻⁵

have studied wood fibre filled plastic composites. Song and Hwang⁶ have reported the mechanical properties of wood fibre filled rubber composites. Yang *et al.*⁷ have studied wood composites based on rice straw and wood particles.

Synthetic thermosetting formaldehyde based resins are typically used as binders in the manufacture of fibreboards using lignocellulosic fibres. Concerns have been raised about the potential health effects of exposure to formaldehyde released from these fibreboards. The International Agency for Research on Cancer has evaluated formaldehyde and classified it as "probably carcinogenic to humans"⁸. These environmental and health concerns contribute to the necessity of investigating new types of adhesives from renewable resources that can decrease or eliminate formaldehyde emission and improve the performance of resulting composite panel products.

There have been several attempts to utilise new adhesives from biomass-derived materials^{9,10}. Lin *et al.*¹¹ have investigated the properties of mouldings made from liquefied wood resins. Vazquez *et al.*¹² have studied the performance of lignin-phenol-

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formaldehyde adhesives in the manufacture of exterior plywood composites.

The wood resin used in this study was obtained from a forest – floor biomass or from recycled or virgin wood by a thermal process. The composition of the wood resin is complex and it contains highly oxygenated organic compounds such as crosslinked phenolics. The wood resin is about four times more expensive than the UF resin.

The objective of this study was to examine the efficiency of wood resin as a binder for wood fibres. This relates to the manufacture of economical and performance-driven composite fibreboards with low levels of formaldehyde emission for indoor applications. Fibreboard composites bonded with 5 wt% wood resin and 5 wt% UF resin were considered as representative fibreboards for the purposes of investigating the effect of cure temperature and time in more detail.

EXPERIMENTAL

Materials

The raw materials for the production of the fibreboard composites were wood fibre, wood resin and UF resin. Recycled soft wood fibre was supplied by Canfibre Group Ltd., Lackawanna, New York. The density of the wood fibre was 1.40 g/cm³ and the moisture content was 7%. The wood resin was supplied by Ensyn Technologies Inc., Greely, Ontario. The natural wood resin was a complex polymer of highly oxygenated organic compounds such as crosslinked phenolics and phenols (90-95%). These were actually depolymerised lignin or pyrolytic lignin. The resin had a very strong

odour of burnt wood and was dark brown to black in colour. The density of the wood resin was 0.73 g/cm³ at 20 °C and it had melting and boiling points of 59° and 135 °C respectively. The liquid UF resin was provided by Dynea U.S.A. Inc., Oregon. The UF resin was water white to opaque. Its density was 1.23 – 1.34 g/cm³ and the boiling point was ~100 °C. The UF resin contained <0.1% by weight of free formaldehyde. Chromotropic acid disodium salt (4,5-Dihydroxy-2,7-naphthalene disulfonic acid disodium salt) and sulfuric acid were supplied by Fischer Scientific, Nepean, Ontario.

Wood Fibre Characterisation

Fibre length distribution, curl index distribution and coarseness of the wood fibres were measured using a fibre quality analyser, FQA (Op Test Equipment Inc., Hawkesbury, Ontario). The FQA comprised of hydraulic, optical and image processing systems. A dilute suspension of wood fibres was transported to the optical and image systems by a sheath flow cell that oriented the fibres into a thin, nearly two-dimensional (2-D) plane. In the tapered region of the cell, the fibres were gradually oriented and positioned by the flow fields imposed by the cell taper. The image detection system consisted of a 2-D 256 × 256 pixel CCD camera. Its resolution and magnification corresponded to a pixel size of about 35 µm.

Preparation of Composite Fibreboards

The soft wood fibre was blended with powder wood resin and/or liquid UF resin according to the formulation given in Table 1, using a rotating drum laboratory blender with a rotation speed of 40 rpm. The solid flakes of wood resin were ground into fine particles (< 1 µ) and mixed with wood fibres.

Table 1. Composites prepared with different ratios (by weight) of wood resin and UF resin under various cure conditions (Pressure 7 MPa)

Compositions and cure conditions	Fibreboard							
	P10-200	P7-200	P5-200	P3-200	P0-200	P5-220	P5-180	P5-200-20
Wood fibre	90	90	90	90	90	90	90	90
Wood resin	10	7	5	3	0	5	5	5
U F resin	0	3	5	7	10	5	5	5
Cure temperature (°C)	200	200	200	200	200	220	180	200
Cure time (min)	10	10	10	10	10	10	10	20

First, a preweighed amount of wood fibres and wood resin (sufficient for one fibreboard of dimensions 150 mm×150 mm×5 mm/6 mm) were mixed together in the blender for 1 h. Then liquid UF resin was spread into the wood fibres as very fine droplets using an air-assisted spray atomiser and the mixing was continued for another 1 h. Before spraying UF resin into the fibres, the UF resin was diluted with equal volumes of a 30% urea-water solution. After finishing the blending process, the fibre-resin mix was collected from the drum blender and dried to remove excess water. Then the dried fibre-resin mix was hand-fed into a 250 mm deep by 150 mm by 150 mm deckle box. When all the fibre-resin mix had been put into the deckle box, the mats were manually precompressed and prepared for insertion into the hot-press. Before hot pressing the mat was placed between two aluminium sheets of thickness 10 mm. The moulding of the mats was done using a hydraulic press under various cure conditions (Table 1). The fibreboards were conditioned for 24 h at 20 °C and 25±2% relative humidity (RH) and their density was determined before analysis of the physical properties.

Measurement of Mechanical Properties

Mechanical properties of the experimental fibreboards were determined in accordance with ASTM D1037 standards. Three-point static bending (modulus of rupture, MOR and modulus of elasticity, MOE) and tensile strength-parallel-to-surface tests of the specimens (dimensions, 12 mm by 150 mm) were performed using a Zwick Universal Testing Machine- Z 100 (Zwick GmbH & Co., Ulm, Germany). The tensile strength-perpendicular-to-surface (i.e., internal bond strength) of the specimens (dimension, 50 mm by 50 mm) was measured using the Zwick UTM. For the internal bond (IB) strength, specimens were attached to aluminium blocks with a hot-melt adhesive (Mastercraft Canada, Toronto), allowed to cool, and then tested in the Zwick UTM. The samples were pulled in the through-thickness direction or across the surface of the board until they failed at a loading speed of 3 mm/min. The un-notched Izod impact testing of the samples was carried out using a Tinius Olsen (92T Impact TM) according to ASTM D 256. The testing machine was equipped with an internal processor to calculate the absorbed energy in Joules.

Dimensional Stability Studies

Thickness swelling and water absorption measurements were carried out in accordance

with ASTM D 1037. The specimens (150 mm by 150 mm) were immersed in distilled water for 24 h at 20 °C and then removed and wiped to remove excess water. The percentage thickness swelling and water absorption of the samples were calculated on a conditioned thickness and weight basis.

For the linear hygroscopic expansion tests, the samples (20 mm by 150 mm) were conditioned at relative humidities of 25±2% and 90±2% at 20 °C for 24 h and the linear expansion was calculated as a percentage.

Analysis of Resin Distribution in Composite Fibreboard

The technique of density profiles was adopted to investigate the resin distribution in composite fibreboards. The density profiles of the composites (50 mm by 50 mm) were determined using a QMS Density Profiler x-ray scanning system-Model QDP-01x (Quintek Measurement Systems, Inc., Knoxville, Tennessee). The theory of this equipment is based on the relationship between x-ray attenuation and the density of the material.

Evaluation of Formaldehyde Emission

The formaldehyde emission from the fibreboard composites was evaluated in accordance with ASTM D6007-02 standards. In performing formaldehyde emission tests, a 1 litre glass chamber with an inlet and an outlet was used. The fibreboard was placed inside the glass chamber at 20 °C and a stream of fresh air with velocity 0.5 m/s was passed through it for 24 h. To achieve a measurable rate of formaldehyde emission, the fibreboards were first cut into small pieces (150 mm × 15 mm × 5 mm) to increase the surface area. The formaldehyde released from the fibreboard surface was absorbed in ice-cold water. The concentration of formaldehyde was determined by a chromotropic acid test followed by spectrophotometric analysis using a UV-visible recording spectrometer-UV 160, (Shimadzu Corporation, Kyoto, Japan)¹³.

RESULTS AND DISCUSSION

Wood Fibre Characterisation

It is generally believed that the mechanical performance and dimensional stability of fibreboard composites depend primarily on the characteristics of the individual fibres and the manner in which they are consolidated. The length and curl index

distribution of wood fibres obtained by the FQA are presented in Figures 1 and 2 respectively. (The curl index is the deviation from straightness of the fibre axis). They become curly during pulping, mixing and refining when exposed to bending and axial compressive stresses. The curl index is defined as

$$\text{Curl index} = \frac{\text{Fibre contour length}}{\text{Longest dimension}} - 1$$

The wood fibres exhibited a wide distribution of lengths, ranging from 0.05 to 4 mm. The average fibre length was 0.74 mm. There were about 2.5%

wood fibres with lengths below 0.1 mm; 25% of wood fibres had lengths in the range of 0.1 to 0.2 mm; 48% of wood fibres had a length between 0.2 and 1 mm and 20% had lengths in the range 1 to 2 mm.

The wood fibres used in the present investigation were comprised mainly of soft wood fibres, which were very weak and short (average length, 0.74 mm) compared to hard wood fibres and agricultural fibres. It is probable that weak and short fibres produce fibreboard composites with novel and beneficial properties because of efficient fibre-to-fibre stress transfer, which is affected by many peripheral variables such as adhesion, board density and

Figure 1. Length distribution of wood fibres by FQA

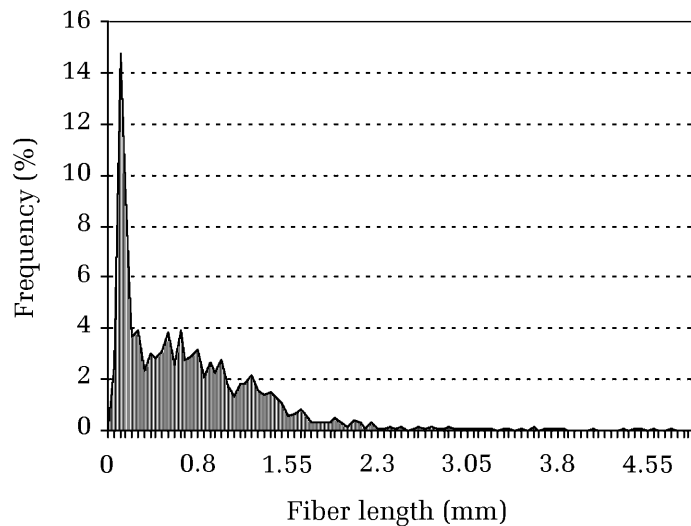
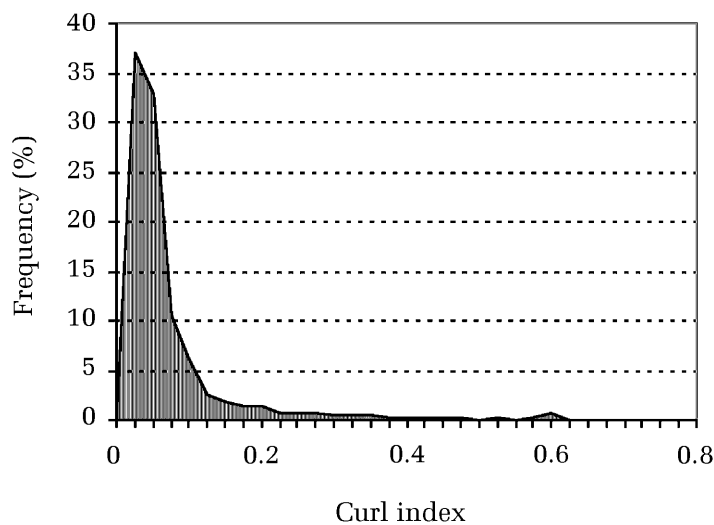


Figure 2. Curl index distribution of wood fibres by FQA



fibre packing. It has been reported by Moss and Retulainen¹⁴ that the addition of fine fibres to Kraft paper increased the strength by filling the voids and thus providing a greater degree of bonding and more efficient fibre-to-fibre stress transfer.

Figure 2 reveals that the wood fibres had a narrow distribution of curl indices ranging from 0 to 0.6. There were about 37% of wood fibres with curl index below 0.025; 33% of wood fibres with indices in the range of 0.025 – 0.05; 17% in the range from 0.05 to 0.1 and 8% with curl index in the range 0.1 – 0.2. The mean curl index was about 0.065.

It is important to note that the observed curl of the wood fibres was affected by, and additional fibre distortions were introduced during, hot processing of the fibre-resin mats. The FQA exhibited an average coarseness of wood fibres of about 0.14 mg/m. In all fibreboards, the fine wood fibres were randomly oriented and the effect of orientation of the fibres was expected to have an insignificant effect on the fibreboard properties.

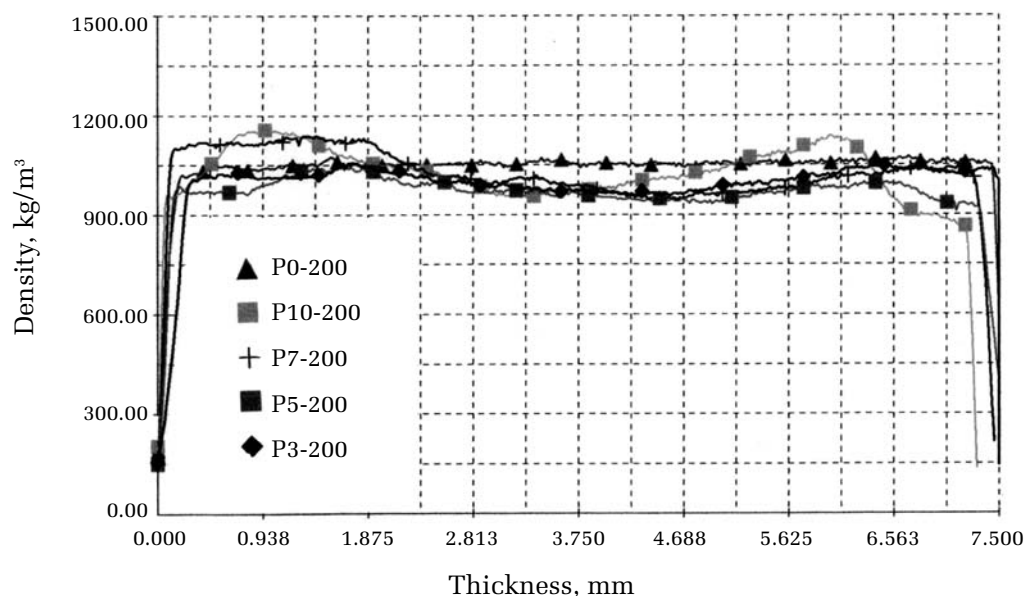
Resin Distribution

The structure and properties of the final composites are governed not only by the properties of the wood fibres but also by the distribution of small resin

spots¹⁵⁻¹⁹. The density profile obtained by x-ray scattering was used to measure the resin distribution. The fine powder particles (<1 µm) of solid wood resin and fine droplets of liquid UF resin were mixed with fluffy wood fibres using a conventional rotating drum laboratory blender. The optimisation of resin distribution depends on the powder particle size of the wood resin, the droplet size of the UF resin and the blending process. It was observed that the viscous nature of the UF resin resisted the formation of fine droplets in the air-assisted atomiser and resulted in poor wettability and low penetration of the UF resin into the wood fibres. Thus the UF resin was diluted with an equal volume of a 30% urea-water solution and applied to the fluffy wood fibres in order to optimise the resin distribution.

The panel density has a direct impact on the properties of the final composites. The amount and conditions of the raw materials in the mat, together with the pressing conditions, determine the average density of the fibreboard composites. The horizontal density profiles of the fibreboard composites bonded with wood resin and/or UF resin are shown in Figure 3. It was found that the fibreboard composites bonded with UF resin and mixed resin showed uniform density distribution through the panel thickness. On the other hand the fibreboards bonded with only wood resin exhibited

Figure 3. Density profiles obtained by QMS Density Profiler of the fibreboard composites



a varying density through the fibreboard thickness. The density profiles indicate that the wood resin distribution in wood fibres was poor compared with UF resin distribution.

The distribution of wood resin can however be optimised by using it in combination with liquid UF resin. All composites prepared from wood fibres bonded with wood resin and/or UF resin showed average densities in the range of 1000 to 1100 kg/m³ (Tables 2 and 3). The fibreboards thus prepared can be classified as high density fibreboard (HDF).

Flexural Properties

The flexural properties such as modulus of rupture (MOR) and modulus of elasticity (MOE) or stiffness of the various fibreboard composites bonded with different blends of wood resin and UF resin (total resin content was 10% always) are summarised in Table 2. The fibreboard composite (P10-200) bonded only with wood resin exhibited lower average flexural strength and modulus (MOR, 43MPa and MOE, 2.3 GPa) than those composites (P0-200) bonded with UF resin (MOR, 62 MPa and

Properties	Fibreboard				
	P10-200	P7-200	P5-200 ^a	P3-200	P0-200
Density (kg/m ³)	1050	1120	1100 (1100)	1060	1010
MOR (MPa)	43	55	58 (60)	61	62
MOE (GPa)	2.3	5.0	4.9 (4.9)	4.8	4.6
Tensile strength, parallel to surface (MPa)	22	31	30 (32)	31	28
Tensile strength, perpendicular to surface (MPa)	0.51	0.58	0.61 (0.58)	0.57	0.47
Izod impact strength (J/m) (un-notched)	54	53	59 (58)	57	66
Linear hygroscopic expansion, 25% to 90% RH, (%)	0.33	0.35	0.32 (0.33)	0.29	0.35
Thickness swelling - 24 h (%)	23	21	24 (24)	18	28
Water absorption - 24 h (%)	32	27	30 (28)	24	39
Formaldehyde emission (µm/m ² /day)	10.4	10.6	11.5	10.6	13.2

^a Values in parenthesis indicate the properties of a fibreboard composite (P5-200-20) bonded with 5% wood resin and 5% UF resin at the cure time of 20 min

Properties	Fibreboard		
	P5-180	P5-200	P5-220
Density (kg/m ³)	1110	1100	1060
MOR (MPa)	34	58	62
MOE (GPa)	2.8	4.9	4.8
Tensile strength, parallel-to-surface (MPa)	24	30	32
Tensile strength, perpendicular-to-surface (MPa)	0.35	0.61	0.63
Izod impact strength (J/m)(un-notched)	53	59	56
Thickness swelling - 24 h (%)	42	24	18
Water absorption - 24 h (%)	48	30	28
Linear hygroscopic expansion, 25% to 90% RH, (%)	0.47	0.32	0.30

MOE, 4.6 GPa). A significant improvement in the flexural properties was observed when the wood resin was partially replaced by UF resin. Figures 4 and 5 show that the experimental MOR and MOE values of the fibreboard composites bonded with a mixture of the two resins (i.e., wood and UF resins) were higher than the calculated values based on the experimental values of the control composites (P10-200 and P0-200).

Even 25% replacement of wood resin by UF resin showed significant increase in the flexural properties of the fibreboard composite. The lower flexural properties of the 10% wood resin bonded

fibreboard (P10-200) were presumably due to the poor distribution of the solid powder resin in the wood fibres.

Holifinger *et al.*⁹ found that the biomass-derived difurfuryl diisocyanate resin, which is more viscous than the structurally similar synthetic diphenylmethane diisocyanate (MDI) resin, gave a lower strength. In general, resins from forest biomass-derived chemicals are solid or highly viscous and it is difficult to achieve a good resin distribution in the fibre composites. When wood resin was applied to wood fibres in combination with liquid UF resin, there was the possibility of improving

Figure 4. Effect of wood resin and UF resin on MOR of the fibreboard composites (■ experimental values and □ calculated values)

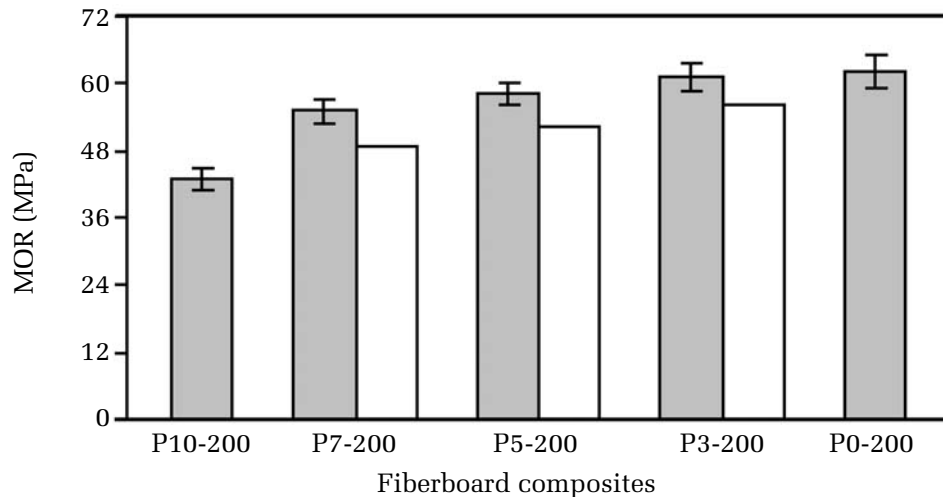
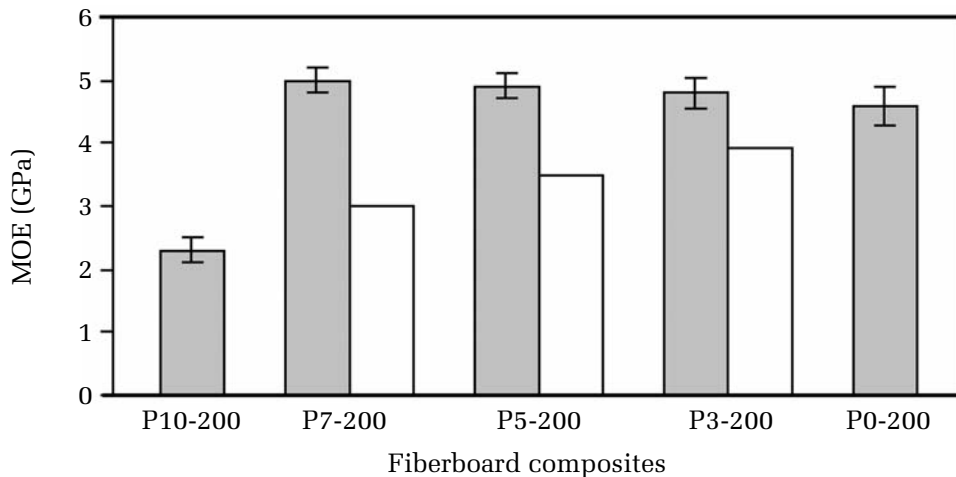


Figure 5. Effect of wood resin and UF resin on MOE of the fibreboard composites (■ experimental values and □ calculated values)



the resin distribution by wetting the fibre surface with liquid resin. The enhanced flexural properties could be attributed to the polycondensation reaction between the phenolic OH groups of wood resin and the hydroxymethyl or methylol groups of UF resin. The results demonstrated that the flexural strength and modulus of the fibreboard composite bonded with wood resin and/or UF resin exceeded the minimum requirements for basic hardboard flexural properties²⁰.

The effect of cure temperature on the flexural properties (MOR and MOE) of those fibreboard composites bonded with 5% wood resin and 5% UF resin at a constant cure time of 10 min and pressure of 7 MPa is shown in Table 3. The best flexural properties were obtained at a cure temperature of 200 °C and there was no significant benefit on increasing cure temperature to 220 °C. On increasing cure temperature from 180 °C to 200 °C the average MOR and MOE values of the fibreboard composites were increased by 70% (from 34 MPa to 58 MPa) and 75% (from 2.8 GPa to 4.9 GPa) respectively. There was no significant change in flexural properties on increasing the cure time from 10 min to 20 min at a constant cure temperature of 200 °C and pressure of 7 MPa (Table 2).

Tensile Strength

The tensile strength-parallel-to-surface (commonly known as tensile strength) values of the fibreboard composites cured at 200 °C are summarised in Table 2. The 10% wood resin bonded fibreboard

(P10-200) exhibited lower tensile strength than 10% UF resin bonded fibreboard, P0-200 (this was a similar trend to that shown by the flexural strength of the composites). On the other hand fibreboards (P7-200, P5-200 and P3-200) consolidated with mixed resins (i.e., both wood and UF resins) exhibited a tensile strength similar to that of 10% UF resin bonded fibreboard and these experimental values were higher than the calculated values based on the data for the P10-200 and P0-200 composites (Figure 6). Increasing the cure time from 10 min to 20 min (Table 2) or increasing the cure temperature from 200 °C to 220 °C (Table 3) had no significant effect on the tensile strength of composites bonded with 5% wood resin and 5% UF resin.

The results (Table 2) show that the tensile strength-perpendicular-to-surface, commonly known as the internal bond (IB) strength, of the 10% wood resin bonded composite (P10-200; IB, 0.51MPa) was marginally higher than that of 10% UF resin bonded (P0-200; IB, 0.47MPa). The internal bond strength values (Figure 7) of the fibreboard composites (P7-200, P5-200 and P3-200) bonded with mixed resin were higher than those of the control fibreboards (P10-200 and P0-200).

This enhancement of the IB strength of composites bonded with mixed resin can be attributed to optimisation of the resin distribution and polycondensation between UF resin and wood resin, as discussed earlier. Chen and Wu²¹ have reported the polycondensation reaction between

Figure 6. Effect of wood resin and UF resin on tensile strength of the fibreboard composites (■ experimental values and □ calculated values)

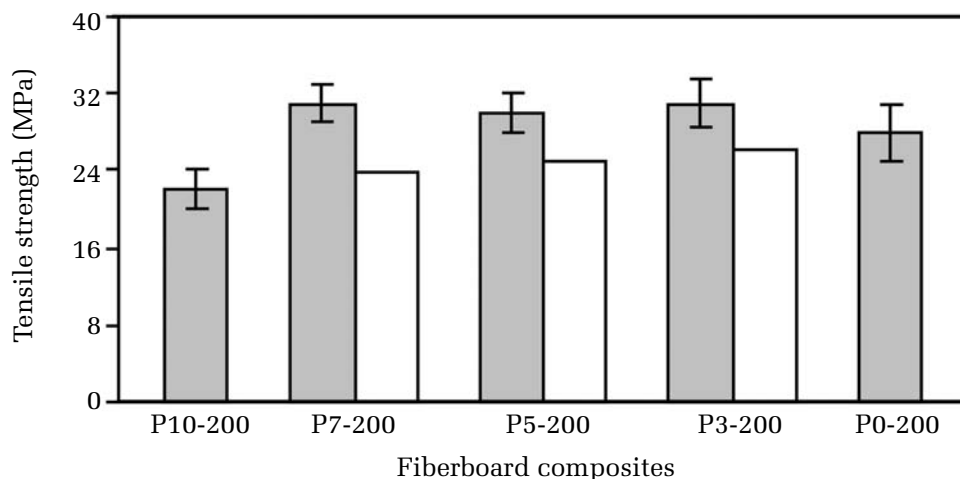
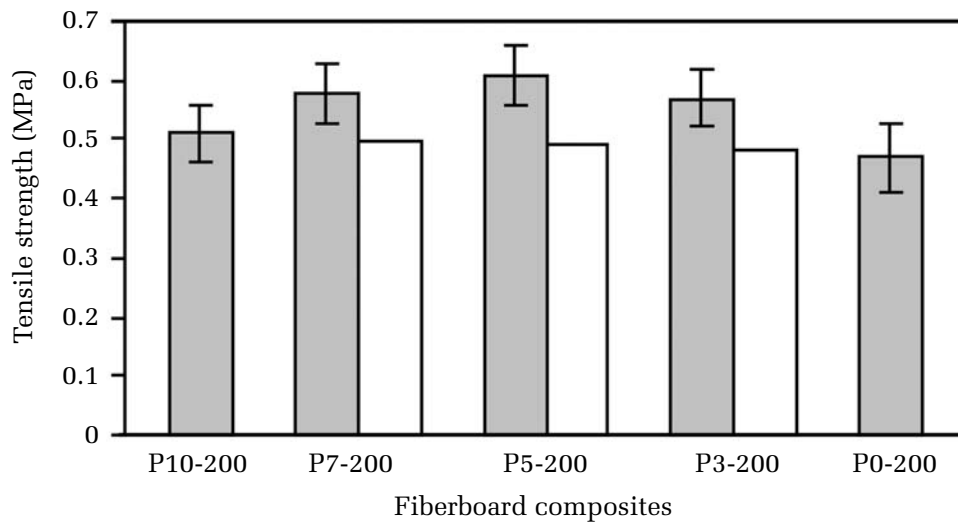


Figure 7. Effect of wood resin and UF resin on internal bond strength of the fibreboard composites (■ experimental values and □ calculated values)



methylol groups in the UF resin and the hydroxyl or carbonyl groups in oxidised lignosulfonate at the cure temperature, and they observed a positive effect on certain particle board properties such as IB strength. The IB strength values of the fibreboard composites were close to the values specified by ANSI-AHA, i.e., 0.62 MPa²⁰.

Increasing the cure time from 10 min to 20 min (Table 2) or the cure temperature from 200 °C to 220 °C (Table 3) had an insignificant effect on the IB strength of fibreboards bonded with 5% wood resin and 5% UF resin.

Izod Impact Strength

The UF resin bonded fibreboard composite (P0-200) exhibited an Izod impact strength (un-notched) of 66 J/m, which was about 18% higher than that of the fibreboard composite bonded with wood resin (P10-200, 54 J/m) (Table 2). The Izod impact strengths of the fibreboard composites (P7-200, P5-200 and P3-200) bonded with mixed resin were intermediate between those of the control composites (i.e., P10-200 and P0-200). The effects of cure time (Table 2) and cure temperature (Table 3) on the impact properties of composites bonded with 5% wood resin and 5% UF resin were insignificant.

Dimensional Stability

The extent of the thickness swelling and water absorption of the fibreboard composites bonded with wood resin or/and UF resin after a 24 h water immersion test are shown in Table 2. The UF resin bonded composite (P0-200) exhibited higher thickness swelling and water absorption than the wood resin bonded fibreboard composite (P10-200). The water resistant properties of fibreboard composites (P7-200, P5-200 and P3-200) bonded with mixed resins were higher than, or similar to that of the wood resin bonded composite. Increasing the cure time from 10 min to 20 min at constant cure temperature and pressure did not have much effect on the water resistance of the composite (Table 2). For 5 mm thickness standard fibreboard, the maximum allowable thickness swell and water absorption values are 25% and 35% respectively²⁰. In the present investigation, the fibreboards bonded with wood resin and mix resin exhibited thickness swelling and water absorption values below the standard requirement. In the case of UF resin bonded fibreboard it exceeded the standard requirement.

The effects of bonding resin type and cure time on the linear hygroscopic expansion of fibreboard composites were marginal (Table 2). As expected, the linear hygroscopic expansion of fibreboard composites bonded with 5% wood resin and 5% UF resin increased on decreasing the cure temperature (Table 3). The maximum requirement of 0.40% for linear expansion for hardboard is specified in the

ANSI-AHA standard²⁰. In the present investigation the fibreboard board composites exhibited linear expansion values below the 0.40% standard value, regardless of resin type.

It was reported that phenol-formaldehyde resin bonded composites showed higher strength than UF resin composites and had less bond degradation in high moisture and high temperature environments²². The wood resin used in the present investigation contained about 90-95% phenolics or phenol compounds. It was also significant that wood resin was more compatible with wood fibre in the formation of fibreboard composites and consequently provided better dimensional stability than UF resin. Humid environmental conditions degraded the adhesive bonds formed by the UF resin. Increasing the cure temperature from 180 °C to 200 °C significantly improved the dimensional stability of the fibreboard composites (Table 3).

Formaldehyde Emission

Formaldehyde is emitted slowly from finished wood-based products during service life, and can cause indoor air pollution²³. Several tannin-based wood adhesives have been developed for the manufacture of low formaldehyde emission wood panels²⁴. Table 2 shows that fibreboards made from wood fibres cause insignificant formaldehyde emission, regardless of the bonding resin type. The UF resin usually used as the bonding adhesive always contains free formaldehyde. The results showed that the wood resin bonded fibreboard exhibited formaldehyde emission similar to that of UF resin bonded fibreboard. This was due to the presence of phenolics or phenol compounds (90 -95%) in wood resin. It has been reported that these oxidisable organic compounds and phenolics compounds may interfere with formaldehyde estimation by the chromotropic acid method, which is the standard method for the formaldehyde estimation^{13,25}. The phenolic OH group of wood resin reacts with the carbonyl group of formaldehyde or other aldehydes and thus interferes in the formaldehyde estimation. Little interference is seen from other aldehydes emitted by wood based composites²⁶.

CONCLUSIONS

- Mechanical properties, dimensional stability and density profiles indicated that the distribution of solid wood resin in fluffy wood fibres could be improved in presence of liquid urea formaldehyde resin.
- A synergism in the mechanical properties of fibreboard composites was found when wood resin was partially replaced by urea formaldehyde resin. The flexural MOR, MOE and tensile strength of the composites exceeded the minimum property requirements of the relevant standard. These improved mechanical properties could be attributed to efficient fibre-to-fibre stress transfer in the composites made from weak, fine wood fibres with length distribution ranging from 0.05 to 4mm and curl index distribution ranging from 0 to 0.6.
- The results indicated that optimisation of the mechanical performance and dimensional stability of the fibreboard composites was achieved at the cure temperature of 200 °C, cure time of 10 min and pressure of 7MPa
- Wood resin possessed unique characteristics that could enable the manufacture of performance-driven fibreboard composites with a low level of formaldehyde emission.

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