THE EFFECT OF SOME PROCESSING VARIABLES ON PROPERTIES OF MIXED HARDWOOD STRANDBOARD[1/]

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Abstract.--The objective of this research was to investigate the effects of three levels each of furnish moisture content (2, 5, 8%), resin non-volatile content (50.8, 54.8, 58.8%), and assembly time (0, 20, 40 minutes) on the strength and dimensional stability of panels made from a combination of mixed hardwoods (60% sweetgum, 40% hackberry, mixed oak species and hickory). Modulus of rupture and internal bond were both significantly affected by furnish moisture content and resin solids percent, increasing with decreasing levels of each. Thickness swell increased significantly with increasing levels of furnish moisture content and resin solids percent. An ovendry-vacuum/pressure/soak cycle resulted in significant reductions in modulus of rupture and internal bond. Assembly time was not significant for any measured property. Linear expansion was not affected by any treatment.

Keywords: hardwood strandboard, resin solids, moisture content, assembly time, MOR, IB, dimensional stability

INTRODUCTION

There is a growing interest by the wood using industry in utilizing hardwood species for structural panel manufacture. Many scientists have reported on extensive research efforts designed to investigate the physical and mechanical properties of wood composite panels manufactured from a variety of single and mixed hardwood species (Hse 1975; Price 1978; Price and Hse 1983; Biblis 1985; Kelly and Price 1985). Numerous board (density, layering, aligning, and resin percent) and process variables (methods of particle generation, press temperature and press closure rate) have been studied. However, no studies dealing with the combined effects of furnish moisture content, resin non-volatile content, and assembly time on the physical and mechanical properties of nonveneered panels manufactured from hardwood species have been reported.

The effects of furnish moisture content have been thoroughly summarized (Kelly 1977). Much of the reported research has been directed toward the interaction of moisture content and press closure rate on the development of the vertical density profile, and subsequent effects on board physical and mechanical properties. Furnish moisture content affects many variables in the gluing process. Insufficient moisture in the wood substrate causes dried-out gluelines and thus reduces the glue-bond quality (Wellons 1980). Koran and Vasishth (1972) found that dried-out gluelines result from water being either evaporated or absorbed by the wood, leaving the resin solids immobolized on the wood surface. Excess moisture in the wood substrate can promote ove rpenetration of the adhesive (Wellons 1980). In all hot-pressed manufactured wood products, high mat moisture content (resulting from either high furnish moisture content or the use of a resin with a low non-volatile content) is likely to cause excess steam/vapor pressure during pressing, resulting in blows when the press is opened. Wood and glueline moisture conditions also affect the rate and degree of resin cure during pressing. A high glueline moisture level can retard solvent loss and subsequent resin cure. At low glueline moisture levels, solvent loss may be too rapid, thus preventing polymer cross-linking.

Resin non-volatile content has been an important variable in many plywood studies, especially related to the effects of moisture

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content and assembly time. Resin non-volatile content, as a function of molecular weight, influences the adhesives ability to wet, to spread, and to penetrate the wood surface. These surface characteristics are largely controlled by the molecular weight of the adhesive. Both over penetration and dryout may be influenced by the adhesive resin non-volatile content, and by the interaction of wood moisture content and resin non-volatile content.

Assembly time has been evaluated extensively in plywood studies, especially as a method of controlling over penetration and dryout (Freeman 1970; Chen and Rice 1973). Longer assembly times may enhance wetting of difficult to wet surfaces. Many dense hardwood species are known to be difficult to wet because of such surface cha racteristics as low surface free energy, extractive con tamination, and low permeability (Nguyen and Johns 1979; Chen 1970; Plomley et al 1976). The effects of assembly time on glue bond performance have not been reported in either laboratory or production manufacture of particle composite panel products. In a laboratory setting it is not uncommon for a multiple board batch of furnish to be blended at one time, and then individual boards felted and pressed. The lag time between felting and pressing the first and last panel can be one hour or more.

The individual effects of furnish moisture content and the resin non-volatile content can affect veneered panel production and properties (Freeman 1970; Chen and Rice 1973). The effect of assembly time has not previously been reported for strandboard applications (nonveneered panels in general). Since each of these three variables are related by their common effect on mat moisture content and moisture distribution, the objective of this study was to incorporate all three variables in an experiment to determine their combined effect on the bonding phenomena in wood particle composites.

MATERIALS AND METHODS

The furnish used in this study was a commercially prepared combination of mixed hardwoods comprised of app roximately 60 percent sweetgum and 40 percent (inclusive) hackberry, mixed oak species and hickory. The furnish was not screened and included a wide range of particle geometries and particle thicknesses. Target flake moisture contents of two, five, and eight percent were attained by drying all material at low heat (60°C) until equilibrated at two percent moisture content. The amount of water necessary to bring the moisture content of a 3-board batch of flakes to either five or eight percent was sprayed as a fine mist onto the flakes in the drum blender used for resin and wax application. Previous experimentation has shown this technique to be accurate and reliable.

A commercially prepared liquid phenol-formaldehyde resin at 58.8 percent non-volatile content and 560 centipoise (Brookfield RVF spindle #2; 25°C) was used in this study. To eliminate cook procedure variability, two portions of the resin were diluted with water to 54.8 and 50.8 percent non-volatile content to produce three resins with three solids levels.

The selected combinations of treatment main effects were randomly assigned to a 3-board batch of furnish. Panels with various treatment combinations were randomly manufactured within a replication. A 3-board batch of furnish was placed in a drum blender and if the treatment called for five or eight percent moisture content, water was sprayed on the furnish at this time. A slack wax was applied at one percent of ovendry furnish weight. Resins were either heated or cooled slightly to maintain a spray viscosity of 250 centipoise (58.8 and 54.8% heated; 50.8% cooled). Resin was applied at a rate of five percent solids based on ovendry furnish weight. The period of resin application was approximately seven minutes. Immediately after resin application, the zero minute assembly time treatment boards were manufactured. The remainder of the furnish was placed in a plastic bag and sealed until needed for the 20 and 40 minute assembly time treatments. All panels were hand-felted in a 16 inch by 16 inch forming box and pressed to a density of approximately 45 pounds per cubic foot. Panels were pressed to thickness using 7/16" steel stops in the press. The total press cycle was six minutes, including 20-25 seconds to stops, 4:45 minutes at maximum pressure, and a 45 second decompression. Press platen temperature was 400°F.

Individual panels were trimmed to approximately 12 inches by 14 inches, and then four-3 inch by 14 inch strips were cut from each panel. After conditioning, these strips were weighed and measured for length, width and thickness to determine strip density variation, to compare to target density, and to use strip density as the covariate in strength and dimensional stability analysis. An edge and a middle strip were randomly assigned to one of two test procedures: The American Society for Testing and Materials (ASTM 1985) D-1037 for evaluating modulus of rupture (MOR) in bending and internal bond (IB), or to a modified American Plywood Association (APA 1980) P1 procedure [ovendry-vacuum/pressure/soak (OD-VPS)] for evaluating thickness swell (TS), linear expansion (LE), and water absorption (WA). IB specimens were removed from the ends of the bending specimens after the bending test. Four IBs per strip (eight/board) were removed from the bending specimens for the ASTM procedure and two IBs per strip (four/board) were removed from bending specimens for the APA-P1 procedure. TS was determined from the average of three thickness measurements on each strip. LE was determined using the brass eyelet method (Heebink 1967). Retention of bending and IB

strength after the OD-VPS cycle were then determined. Dry specimen thickness was used in all calculations of MOR, including those after swelling.

Combinations of furnish moisture content and resin non-volatile content levels resulted in calculated mat moisture contents ranging from 6.1 percent to 12.8 percent (Table 1). Because mat moisture content resulting from these treatment combinations was likely to influence the vertical density profile and subsequent strength properties, the vertical density profile was evaluated for specimens from one replication. A direct scanning gamma densitometer was used to map the density profile on the remaining portion of the bending specimens. A 100 millicurie americium^{241} radiation source was used to make two profile scans on each specimen. Eighteen incremental steps of 0.025 inch were used with a ten second count at each step. This device and its applicability to measuring the vertical density profile in wood composites has been described by Winistorfer et al (1986).

Table 1.-- Calculated mat moisture content for combinations of all levels of furnish moisture content and resin non-volatile content.

FURNISH MOISTURE CONTENT (%)	RESIN NON-VOLATILE CONTENT (%)	CALCULATED MAT MOISTURE CONTENT (%)
2	50.8	6.8
2	54.8	6.1
2	58.8	5.5
5	50.8	9.8
5	54.8	9.1
5	58.8	8.5
8	50.8	12.8
8	54.8	12.1
8	58.8	11.5

This experiment was a complete factorial with three replications, analyzed as a split-split-plot design (fig. 1). Experimental main effects were flake moisture content and resin non-volatile content. Assembly time was the sub-plot treatment applied to a 3-board batch of flakes. A test procedure (ASTM D-1037 or APA-P1) was applied as a sub-sub-plot treatment to compare strength properties before and after the OD-VPS cycle. The sum of squares for main effects and sub-plot treatments were partitioned into two single degree of freedom components: one to estimate the linearity of the relation between the response and the treatment (LIN) and the other to estimate the lack-of-fit of the response to the linear model (LOF) (Chew 1976). An analysis of covariance procedure, using individual test specimen density as the covariate, was investigated for all strength and dimensional stability properties. Analysis of covariance combines the features of analysis of variance and linear regression to adjust means for each measured property to a common test specimen density. These least-squares-adjusted treatment means were then compared by one degree of freedom linear contrasts. Eighty one 16 inch by 16 inch laboratory panels were manufactured for this study.

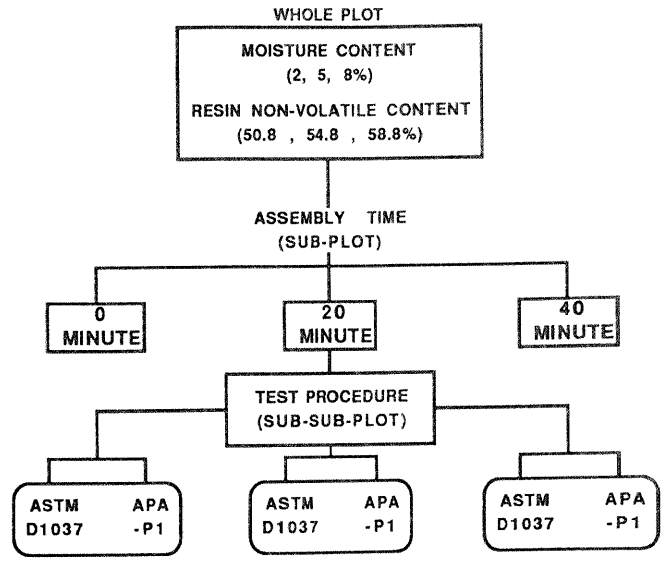

Figure 1.-- Flow chart of experimental effects depicting a complete factorial analyzed as a split-split-plot design. Shown are levels of the whole-plot (moisture content and resin non-volatile content), the sub-plot (assembly time), and sub-sub-plot (test procedure). There were three replications of all treatments for a total of 81 panels.

RESULTS AND DISCUSSION

Test specimen density (the covariate) was significant for all measured responses, except linear expansion, and all experimental treatments, except assembly time (Table 2). Consequently, all means were adjusted to a common test specimen density and are shown as least-squares-adjusted treatment means. Linear expansion values and all measured response variables for assembly time are also shown adjusted (using density covariate) for all treatment effects. Pertinent physical property data for all treatment effects are shown in Table 2.

Table 2.--Properties[1] of 7/16" homogeneous strandboard made from mixed hardwood species (approximately 60% sweetgum and 40 hackberry, mixed oak species and hickory.)

	Modulus of Rupture (Psi) Test Procedure[2] (P=0.001)		Internal Bond (Psi) Test Procedure[2] (P=0.001)		Dimensional Stability[3] (%)		
Moisture Content (%)	ASTM D-1037	APA-P1	ASTM D-1037	APA-P1	Thickness Swell	Water Absorption[4]	Linear Expansion
2	3252	679	119	73	34.0	95	0.48
5	3257	647	96	34	34.6	94	0.43
8	3119	486	74	9	36.0	93	0.55
Linear	(P=0.032)[5]		(P=0.001)		(P=0.011)	(P=0.009)	(P=0.327)
Lack-of-Fit	(P=0.192)		(P=0.150)		(P=0.540)	(P=0.843)	(P=0.147)
Standard Error[6]	255.12		26.27		3.45	3.41	0.003
Resin Solids Percent (%)							
50.8	3353	621	100	44	34.1	93	0.45
54.8	3125	599	94	37	34.8	95	0.47
58.8	3149	591	95	36	35.7	94	0.56
Linear	(P=0.058)		(P=0.028)		(P=0.027)	(P=0.148)	(P=0.116)
Lack-of-fit	(P=0.135)		(P=0.144)		(P=0.842)	(P=0.072)	(P=0.504)
Standard Error[6]	255.12		26.27		3.45	3.41	0.003
Assembly Time (minutes)							
0	3113	675	88	43	35.1	94	0.53
20	3281	680	98	42	35.1	94	0.47
40	3038	653	93	43	34.4	94	0.46
Linear	(P=0.539)		(P=0.207)		(P=0.096)	(P=0.410)	(P=0.465)
Lack-of-fit	(P=0.322)		(P=0.533)		(P=0.246)	(P=0.846)	(P=0.646)
Standard Error[6]	223.89		23.34		2.10	2.17	0.003

1/ All values adjusted to a board density of 47.3 lb/f^3 by analysis of covariance, using test specimen density as the covariate for each measured property.
2/ Mean values are shown for modulus of rupture and internal bond for both test procedures. The P-value indicates the probability of a greater F-value for the comparison test procedure. The APA-P1 procedure is an ovendry-vacuum/pressure/soak cycle.
3/ Dimensional stability values determined at the end of the APA-P1 procedure.
4/ Water absorption values reported only to show saturation of specimens during the APA-P1 procedure.
5/ The p-value indicates the probability of a greater F-value for a linear and lack-of-fit effect partitioned for each treatment.
6/ Estimated by the mean square for error from the analysis of covariance.

Moisture Content

Modulus of Rupture (MOR)

MOR was significantly (P=0.032) affected by furnish moisture content, MOR decreasing with increasing furnish moisture content. Extremes in furnish moisture content are known to be deliterous to bond quality (Freeman 1970; Chen and Rice 1973). Calculated mat moisture contents, for the levels of combined mat moisture content and resin non-volatile content, were in the range of 5.5 to 12.8 percent (Table 1). The furnish moisture content level of 8 percent, either considered individually or in combination with any level of resin non-volatile content, resulted in a high (11.5 to 12.8 percent) mat moisture content before pressing, possibly indicating poor bond development due to either overpenetration or undercure in the core region. No blows were detected upon press decompression for the six minute press cycle, despite the high moisture content levels used in this study.

MOR measured after the OD-VPS cycle also showed a significant (P=0.032) linear decrease with increasing furnish moisture content. Bond development and bond durability are greatly reduced with high mat moisture levels.

Internal Bond (IB)

Increasing furnish moisture content resulted in significant (P=0.001) reductions in IB strength. A significant linear response, accounting for 98 percent of the reduction in IB strength, was noted for this trend. IB strength is mostly dependent on board density and bond development, usually in the central core region of the panel. Increasing mat moisture content likely inhibited bond development in interior panel layers by affecting the internal board temperature during pressing. The range of IB strengths for treatment combinations in this study are similar to those reported by Price and Hse (1983) and Kelly and Price (1985); both studies used individual and mixed combinations of dense hardwoods.

The OD-VPS cycle resulted in a significant loss of IB strength. The two percent furnish moisture content level had an IB strength of 73 pounds per square inch (psi) after the OD-VPS cycle (61% retention), perhaps an acceptable value even for tests conducted in the dry condition (ASTM D-1037) considering the species mix and board density. IB retention for the five and eight percent furnish moisture levels were 35 percent (34 psi) and 12 percent (9 psi) respectively; these values are unacceptable. These low IB retention values suggest that increasing the furnish moisture content inhibits resin cure and bond formation.

Dimensional Stability

Water absorption (WA) as measured after the OD-VPS cycle showed a significant (P=0.009) increasing response to decreasing furnish moisture content levels. WA values are shown primarily to indicate saturation of the specimen during the OD-VPS cycle. No sample reached complete saturation during the cycle, based on weight change from the ovendry condition. Higher furnish moisture content levels may have led to better mat consolidation during pressing, possibly minimizing water infiltration through the board surface and edges.

Thickness swell (TS) increased with increasing furnish moisture content. This result is contrary to the general trend found in the literature as summarized by Kelly (1977). Density profiles for all treatments showed that with increasing furnish moisture content levels the density of the board surface and subsurface layers increased (Figure 2). Vital and Wilson (1979) showed TS to increase with increasing board density. Because board density was not an experimental variable in this study, it is difficult to separate the effects of changes in the density profile and the possibility of reduced or incomplete resin cure due to excessive furnish moisture on TS. It is likely that these two phenomena had a synergistic effect on increased TS with increasing furnish moisture content.

Linear expansion (LE) showed no significant response to changes in furnish moisture content levels. Price and Hse (1983) found LE to increase with board density and also with increasing furnish density. Prior to adjusting LE values to a common test specimen density by an analysis of covariance, furnish moisture content was significant for LE. Reporting this significance would mask the relationship between LE and furnish moisture content.

Resin Non-Volatile Content

Modulus of Rupture (MOR)

The significance (P=0.058) of resin non-volatile content for MOR was slightly above the usual significance level (P=0.05) but does suggest a trend: MOR increased with decreasing levels of resin non-volatile content. This trend is probably a function of surface densification and resin distribution. As resin non-volatile content level decreased, mat moisture content increased (Table 1). Consequently, greater surface consolidation/densification was achieved with the lower (50.8%) non-volatile content level (fig. 2). Also, resin distribution is directly related to the volume of resin sprayed. Therefore, resin distribution most likely improved as resin non-volatile content decreased.

MOR response to resin non-volatile content after the OD-VPS cycle showed increased retention with decreased resin non-volatile content. The range of MOR retention for the main effect resin non-volatile content was much smaller than the range of retention values measured for the main effect furnish moisture content. This may imply that, when considered individually, for the levels of treatments used in this study, furnish moisture content has a greater effect on bond durability and strength retention than resin non-volatile content.

Internal Bond (IB)

Resin non-volatile content was also significant (P=0.028) for IB: IB increasing with decreasing levels of resin non-volatile content. While each level of resin non-volatile content is statistically different, the pratical significance of a range of six psi for the dry-tested samples (ASTM) and eight psi for the OD-VPS tested samples is doubtful.

The OD-VPS cycle resulted in significant reductions in IB strength for all levels of resin non-volatile content. As was found for MOR, the range of IB values in response to resin solids percent treatment levels (for both test procedures) was less than that found for furnish moisture content levels. Both of these conditions again suggest that, for the levels of treatments used in this study, furnish moisture content has a greater impact on bond development and durability than resin non-volatile content.

Dimensional Stability

Increasing resin non-volatile content yielded significantly (P=0.027) greater TS values, possible indicating successively better resin distribution with decreasing resin non-volatile content. WA and LE were not influenced by resin non-volatile content. Average values for TS, WA, and LE in response to resin non-volatile content levels were similar to values found for furnish moisture content.

Assembly Time

Strength and dimensional stability properties were not significantly affected by assembly time. Assembly time was included in this study on the premise that it is an integral part of the manufacturing process. Also of interest were the fundamental interactions of furnish moisture content, resin non-volatile content and assembly time. Placing the furnish in sealed plastic bags after blending for the duration of the assembly time treatment may have prevented any evaporation of the solvent and inhibited a dryout-like condition. However, this procedure should have promoted adhesive penetration into the substrate. Further study is recommended, using a wider range of assembly time treatments and leaving the furnish unbagged to promote the desired effects.

OTHER CONSIDERATIONS

The interactions of all treatment effects were investigated. For MOR and IB the interactions furnish moisture content by test procedure and assembly time by test procedure were significant (P=0.022 and P=0.013, respectively). Overall, increasing furnish moisture content resulted in decreasing strength properties. When evaluated after the OD-VPS cycle, the strength retention was progressively worse at each increased furnish moisture content level. This interaction suggests poor bond durability for MOR and IB, in response to increased furnish moisture content.

The technique used to establish furnish moisture content levels may have accentuated some conditions. It is likely that a significant moisture gradient was present for individual particles in the furnish, the particle surface being at a higher moisture content than the particle interior. This gradient was likely greatest for the eight percent furnish moisture content level, being further enhanced by the 50.8 percent non-volatile resin application level.

The interaction assembly time by test procedure is probably significant as influenced by the significance of the test procedure. Assembly time was not significant as a main effect and practical significance of this interaction for either MOR or IB is doubtful.

For the range of mat moisture contents used in this study greater differences in strength and dimensional stability properties were expected (Table 2). Literature reviewed by Kelly (1977) indicated bending properties increased up to 20 percent when increasing furnish moisture content in the range from six percent to 12 percent. In this study, both MOR and IB decreased with increasing furnish moisture content. The response of dimensional stability properties to furnish moisture content was also different than most others reported (Kelly 1977). The results of this study suggest that other factors may be involved in bonding dense hardwoods (compaction ratio, moisture migration through dense hardwood flakes, pressing induced particle surface damage).

Density profiles were evaluated for all treatments to examine the effects of furnish moisture content levels on density development. Increasing furnish moisture content resulted in increasing density of the face layers. Low furnish moisture content levels resulted in more uniform profiles. Figure 2 shows profiles averaged over all treatments for calculated

prepress moisture content values of 5.5, 9.1 and 12.8 percent. Even though increased furnish moisture content resulted in denser face layers (steeper profile), bending strength was not responsive to these profile changes. Increased furnish moisture was apparently more detrimental to bond development and strength properties than the advantageous effects of increased face layer density.

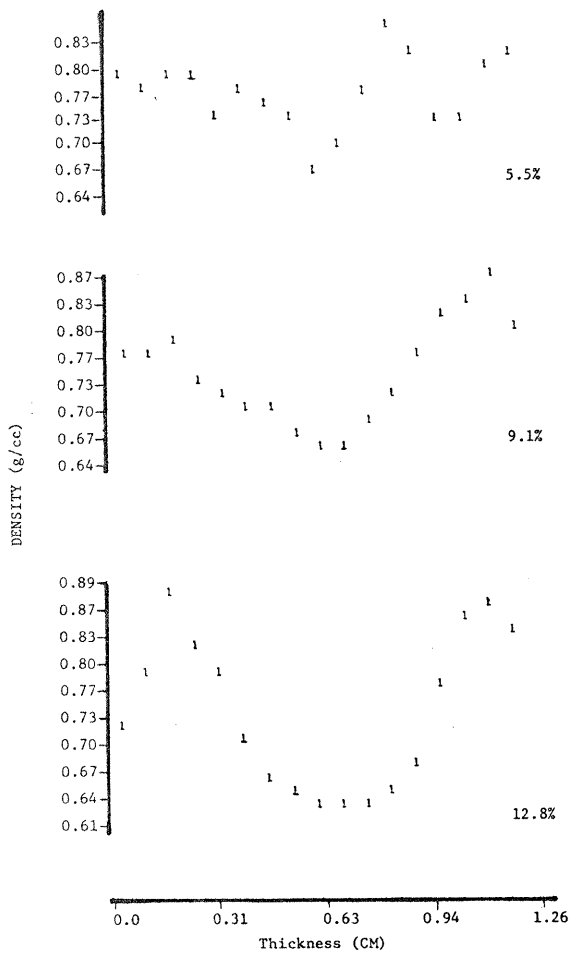

Figure 2.--Density profiles for furnish moisture content levels 5.5%, 9.1%, and 12.8%.

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