

# MECHANICAL PROPERTIES OF MDF AS A FUNCTION OF DENSITY AND MOISTURE CONTENT

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## ABSTRACT

This study examined the effect of medium density fiberboard (MDF) density and moisture content on MDF moduli of elasticity  $E_1$ ,  $E_3$ , shear modulus,  $G_{13}$ , and Poisson's ratios  $\nu_{12}$  and  $\nu_{13}$ . The relation of all parameters with density was determined from MDF panels without density profile with average density levels of 540 kg/m<sup>3</sup>, 650 kg/m<sup>3</sup>, and 800 kg/m<sup>3</sup>. The relation with moisture content was determined from specimens conditioned to 50%, 65%, and 80% relative humidity. Panel  $E_1$ ,  $E_3$ , and  $G_{13}$  increased with density increase and decreased with moisture content increase. At each nominal density level, the values of  $E_1$  were much higher than the values of  $G_{13}$ , which in turn were higher than the values of  $E_3$ . The effect of density and moisture content on the Poisson's ratios was not significant.

**Keywords:** MDF (medium density fiberboard), moduli of elasticity, shear modulus, Poisson's ratios, moisture content, density.

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## INTRODUCTION

The mechanical properties and the dimensions of medium density fiberboard (MDF) are strongly affected by moisture content (M) (e.g. Chow 1976; Halligan and Schniewind 1974; Dong *et al.*, 1992). The effect of an (M) change on panel flatness is difficult to predict because of the characteristic variation of the density level throughout the thickness, or vertical density profile. The level of densification (compaction ratio) of each layer, its distance from the central plane, and its thickness determine its specific effect on the overall panel properties. There is usually no difference in fiber geometry and resin content throughout MDF panel thickness, along and across the forming direction; therefore, the differences among the layers are basically determined by the compaction ratio. The contribution of each layer and the dynamic effect of M on warping can be calculated by a numerical model (Cloutier *et al.* 2001). To achieve this goal, the properties of each MDF layer as a function of M and density need to be known.

*Mechanical model of warping*

The components of the stress tensor for an elastic orthotropic and hygroscopic material undergoing moisture changes ( $\Delta M$ ) can be expressed as follows if the principal material directions coincide with the principal directions of the coordinate system used (Fig. 1):

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1-\nu_{23}\nu_{32}}{E_2E_3S} & \frac{\nu_{21}+\nu_{23}\nu_{31}}{E_2E_3S} & \frac{\nu_{31}+\nu_{21}\nu_{32}}{E_2E_3S} & 0 & 0 & 0 \\ \frac{\nu_{21}+\nu_{23}\nu_{31}}{E_2E_3S} & \frac{1-\nu_{31}\nu_{13}}{E_1E_3S} & \frac{\nu_{23}+\nu_{21}\nu_{13}}{E_1E_2S} & 0 & 0 & 0 \\ \frac{\nu_{31}+\nu_{21}\nu_{32}}{E_2E_3S} & \frac{\nu_{23}+\nu_{21}\nu_{13}}{E_1E_2S} & \frac{1-\nu_{21}\nu_{12}}{E_1E_2S} & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & G_{13} & 0 \\ 0 & 0 & 0 & 0 & 0 & G_{12} \end{bmatrix} \begin{Bmatrix} \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{pmatrix} \\ \begin{pmatrix} \beta_1\Delta M \\ \beta_2\Delta M \\ \beta_3\Delta M \end{pmatrix} \\ \begin{pmatrix} \varepsilon_{23} \\ \varepsilon_{13} \\ \varepsilon_{12} \end{pmatrix} \end{Bmatrix} \quad (1)$$

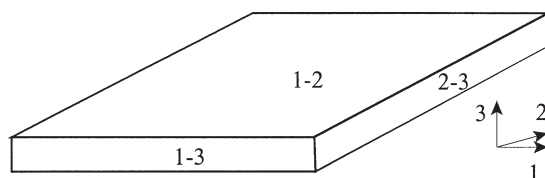


FIG. 1. Schematic drawing of a MDF specimen with axis definition.

$$\text{with } S = \frac{1}{E_1E_2E_3} (1 - 2\nu_{21}\nu_{32}\nu_{13} - \nu_{13}\nu_{31} - \nu_{23}\nu_{32} - \nu_{12}\nu_{21}) \quad (2)$$

where:  $\sigma_{ij}$  = stress components vector;  
 $\varepsilon_{ij}$  = strain components vector;  
 $\beta_i$  = shrinkage/swelling expansion coefficient vector ( $\%^{-1}$ );  
 $\Delta M$  = moisture content change (%);  
 $E_i$  = moduli of elasticity (Pa);  
 $G_{ij}$  = shear moduli (Pa);  $\nu_{ij}$ : Poisson's ratios.

For isotropic materials,  $E_1=E_2=E_3=E$ ;  $G_{23}=G_{13}=G_{12}=G$ ;  $\nu_{12}=\nu_{13}=\nu_{21}=\nu_{23}=\nu_{31}=\nu_{32}=\nu$ ; and  $\beta_1=\beta_2=\beta_3=\beta$ . Medium density fiberboard can be assumed as plane isotropic (Bodig and Jane 1993). Assuming (1–2) to be the plane of isotropy, one could write:  $E_1=E_2$ ,  $G_{23}=G_{13}$ ,  $\nu_{12}=\nu_{21}$ ,  $\nu_{23}=\nu_{32}=\nu_{13}=\nu_{31}$ , and  $\beta_1=\beta_2$ . Moreover, the shear moduli  $G_{12}$  can be obtained from  $E_1$  and  $\nu_{12}$  as follows:

$$G_{12} = \frac{E_1}{2(1+\nu_{12})} \quad (3)$$

Consequently, seven independent parameters need to be determined experimentally as a function of density and M:  $E_1$ ,  $E_3$ ,  $\nu_{12}$ ,  $\nu_{13}$ ,  $G_{13}$ ,  $\beta_1$  and  $\beta_3$ . Limited literature data are available on the above properties for MDF although they are necessary to develop a model of hygromechanical warping of this type of composite panel.

*Determination of the modulus of elasticity in the 1–2 plane,  $E_1$* 

In industrial practice, the modulus of elasticity (MOE) is determined in bending (e.g. ANSI,

A208.2–2001 MDF) since it corresponds to specific end uses such as shelving or tabletops. For this reason, there are only limited data available on  $E_1$  measured in tension parallel to the panel plane. The values obtained with bending tests are not in all cases suitable for modeling purposes since deflection caused by shear sometimes can not be eliminated (Bodig and Jane 1993). Still, it can be expected that  $E_1$  will show trends similar to bending MOE. Based on the publications available for MOE,  $E_1$  should decrease with M-increase (e.g. Watkinson and Gosliga 1989) and increase with density-increase (e.g. Boëhme 1980).

*Determination of the modulus of elasticity perpendicular to the 1–2 plane,  $E_3$*

This property is not needed in daily production. This is probably why no literature data could be found on this property for MDF. In most existing models of wood composites, material isotropy is assumed (e.g. Hunt and Suddarth 1974), which eliminates the need for determining  $E_3$ . This assumption oversimplifies the structure of MDF, a plane isotropic material where  $E_3$  differs from  $E_1$ . Since there are no literature data on  $E_3$ , the published results from tests of modulus of rupture in tension perpendicular to the surface (internal bond tests) can be used for orientation. The published results differ on the effect of M: For particleboard, Halligan and Schniewind (1974) observed that a 15 % increase in M leads to a reduction in IB strength by approximately 60 %; Lee and Biblis (1976) observed only a 7.1 % reduction for similar changes in M; Borchgrevnik (1977) did not find any correlation between M and IB strength for MDF. Most authors did not observe a correlation between density and IB strength (e.g. Suchsland et al. 1978; Chapman, 1979; Boëhme, 1980).

*Interlaminar shear modulus,  $G_{13}$*

The shear moduli of wood composites have been largely determined by torsional vibration (e.g. Nakao and Takeshi 1987; Dong et al. 1992). A torsion shear test has also been applied (e.g.

Shen 1970). However, the interlaminar shear technique (ASTM D 1037–99) has proven suitable for testing small-scale specimens for research purposes. According to Schulte and Frühvald (1996), the interlaminar shear test outperforms other setups since it is simple to realize, does not have a predetermined failure position, and directly determines  $G_{13}$ , while the torsion shear, for example, represents a combination of two shear moduli:  $G_{13}$  and  $G_{23}$ .

Test results obtained with torsional vibration for particleboard (Dong et al. 1992) suggest that for MDF,  $G_{13}$  would probably decrease by about 50 % after immersion for 24 h. Schulte and Frühvald (1996) and Wang et al. (1999) observed that when density increased so does  $G_{13}$ .

*Poisson's ratios,  $\nu_{12}$  and  $\nu_{13}$ .*—Most existing models of elastic behavior of wood composites are one-dimensional and do not use Poisson's ratios. In other models, nominal constant values were adopted for the Poisson's ratios (e.g. 0.30 for particleboard, Bulleit 1985; 0.29 for the longitudinal versus radial deformation in Douglas fir, Tong and Suchsland 1993). No standardized method for determining Poisson's ratio in wood or wood materials was found in the literature. The microscopic deformations involved are exclusively recorded by means of strain gauges (Neumüller and Niemz 1983; Bulleit 1985; Moarcas and Irle 1999; Tang and Lee 1999).

Bodig and Jayne (1993) regarded wood composites as isotropic materials and assumed values both for  $\nu_{12}$  and for  $\nu_{13}$  in the range of 0.3. No other data on  $\nu_{13}$  were found in the literature. Other results published for  $\nu_{12}$  strongly vary. For particleboard, Keylwerth (1958) obtained values between 0.26 and 0.41, while the results of Moarcas and Irle (1999) were in the range of 0.17 to 0.23. If any effect is observed, it might be expected that Poisson's ratios would slightly decrease with M (Tang and Lee, 1999 for flakeboard) and slightly increase with density (Neumüller and Niemz, 1983 for particleboard).

## OBJECTIVE

The objective of this research is to determine MDF mechanical properties  $E_1$ ,  $E_3$ ,  $G_{13}$ ,  $\nu_{12}$ , and

$\nu_{13}$  as a function of density and moisture content at 20 °C.

## MATERIAL AND METHODS

### Material

Green black spruce (*Picea mariana*) chips, a typical raw material for MDF in Eastern Canada, were provided by a local sawmill. The wood chips were reduced to fibers in an industrial-grade Andritz refiner at Forintek Canada Corp., Eastern Laboratory. The fibers were dried to 2% initial M before resin blending. Commercial urea-formaldehyde (UF) resin was provided by Borden Canada.

The calculated quantities of the components were mixed in a laboratory rotary blender. A UF resin (12 % solid resin based on wood oven-dry weight) and slack wax emulsion (1% wax based on wood oven-dry weight) were applied directly to the wood fibers using an air-pressure spray nozzle set parallel to the axis of the blender drum. No catalyst was applied, since the duration of hot-pressing was more than adequate to cure the resin. Typical mat moisture contents of approximately 12.5 % were obtained. The blended fibers were formed on steel caul-plates into one-layer mats of 650 mm x 650 mm by a fiber-felting machine. The mats were manually pre-pressed and then hot-pressed in a Dieffenbacher hot press. The press closing time was 40 to 50 s at a maximum pressure of about 5.4 MPa. The pressure was then reduced to 0.9 MPa and kept constant for 190 s to achieve a core temperature of 120 °C for 70 s and a target thickness of 12 mm. Finally, the pressure was gradually reduced to zero and the press opened within approximately 15 to 20 s.

A total of 39 laboratory 12-mm-thick MDF panels divided into 3 nominal density groups ( $13 \times 540 \text{ kg/m}^3$ ,  $13 \times 650 \text{ kg/m}^3$ ,  $13 \times 800 \text{ kg/m}^3$ ) was produced. Each panel was edge-trimmed (50 mm from each side) to discard the weak area next to the edges. The surface layers of the panels were removed in a planer, and the thickness of the remaining core layer was reduced by sanding to 8 mm. Thus, panels with a flat vertical density profile with dimensions 540 mm x 540 mm were

obtained. This allowed studying the effect of density on the mechanical properties while eliminating the effect of the vertical density profile.

### Methods

*Evaluation of vertical density profile.*—A QMS X-ray density profiler, Model QDP-01X, was used to determine the vertical density profile of each 8 mm-thick panel in order to ensure that the density was homogeneous enough across thickness for the density variation to be considered negligible for modeling purposes (Ganev et al. 2003).

*Mechanical tests.*—All mechanical tests were accomplished with an MTS Alliance RT-50 universal testing machine.

*Modulus of elasticity parallel to the surface,  $E_1$ .*—The modulus of elasticity parallel to the surface  $E_1$  was determined on test specimens with a width reduced in the mid-length according to the ASTM D 1037–99 Standard: Tensile Strength Parallel to Surface. An Instron axial extensometer Gauge Length L 986 attached directly to the specimen (Fig. 2) was used to measure the deformation. For calculating  $E_1$ , the slope ( $\tan \alpha$ ) in the elastic zone was determined from a regression between the stress and the corresponding strain.

*Modulus of elasticity perpendicular to the surface,  $E_3$ .*—The modulus of elasticity perpendicular to the surface  $E_3$  was determined according to the ASTM D 1037–99 Standard: Tensile Strength Perpendicular to Surface. For determination of  $E_3$ , the slope in the elastic zone from a regression between the load and the corresponding deformation was used. Two aluminum blocks were glued to each specimen with dimensions 50 mm x 50 mm x panel thickness using an epoxy hot-melt glue, which allowed for reuse of the blocks. The deformations were measured with the Instron axial extensometer Gauge Length L 986 attached to the aluminum blocks. Tensile modulus of elasticity in the  $x_3$  direction was determined from the slope ( $\tan \alpha$ ) in the elastic zone from a regression between the stress and the corresponding strain. A photograph of

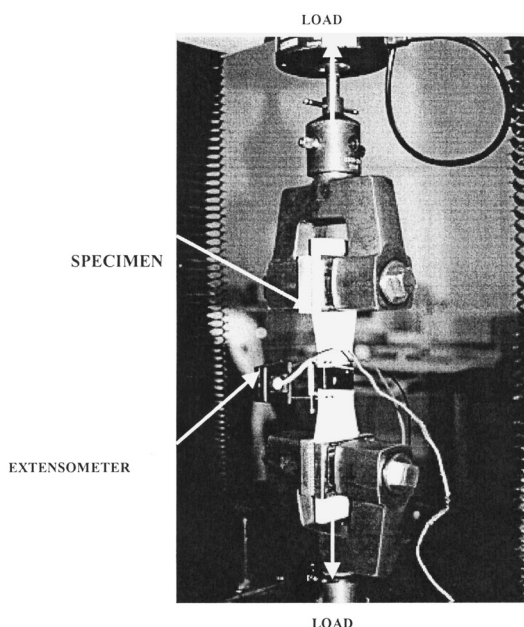


FIG. 2. Setup for determination of  $E_1$ .

the setup used is given in Fig. 3 for the case when the modulus of elasticity of the hardened adhesive was tested. In this case, the aluminum blocks were glued together without an MDF specimen. The test was interrupted when the  $E_3$  of the bond line was observed to exceed four times the largest  $E_3$  values obtained with MDF

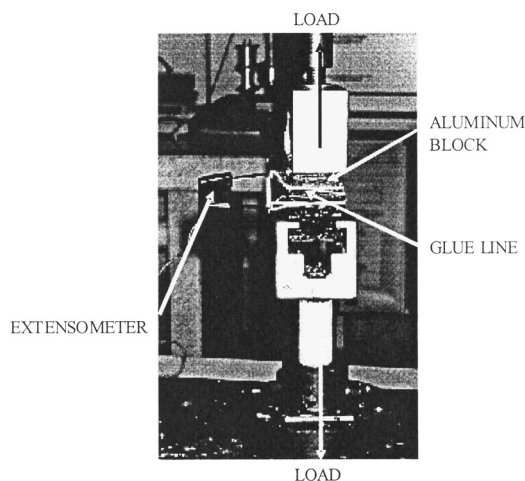


FIG. 3. Setup for determination of  $E_3$ .

specimens and further loading would lead to damage of the load cell. The adhesive rigidity ensured an error level of below 1% and it was assumed that  $E_3$  of the glue and aluminum could be neglected for the range of loads used for the MDF specimens.

**Determination of the interlaminar shear modulus,  $G_{13}$ .**—For determination of the edgewise shear  $G_{13}$ , the setup for the ASTM D 1037–99 method Interlaminar Shear was used. The shear modulus was determined by recording the strain versus load proportion of eight specimens per exposure level in the elastic zone. Two steel plates with a thickness of 20 mm were glued to specimens with dimension 150 mm x 50 mm x 8 mm. The steel plates width and length exceeded specimen width and length by 7 mm and were beveled at 45° on the side to which the force was applied. The steel plates were bonded to the specimens using an epoxy hot-melt glue, which allowed for reuse of the blocks. The edge of the steel plates fitted the groove in the loading blocks. One block was mounted in a unidirectional spherical bearing block so that the load was uniformly distributed across the width of the specimen. The strain between the two steel plates was recorded by a linear variable differential transformer (LVDT) Schlumberger ACR 15 (Fig. 4). For calculation of  $G_{23}$ , the slope ( $\tan \alpha$ ) in the elastic zone was determined from a regression between the shear stress and the corresponding shear strain. As for  $E_3$  it was assumed that  $G_{13}$  of the hardened adhesive exceeded  $G_{13}$  of MDF by a factor of four or more. The tests indicated that also in the case of shear modulus the effect of glue could safely be neglected. The  $G_{13}$  was determined as a ratio of the load at proportional limit and the displacement of one steel plate with respect to the other.

**Poisson's ratios.**—The Poisson's ratios ( $\nu_{12}$  and  $\nu_{13}$ ) were obtained from the setup used for the determination of  $E_1$  as described above. The active ( $\epsilon_1$ ) and the passive ( $\epsilon_2$ ) strains in the plane were recorded by using perpendicular grid type bi-axial strain gauges CEA-06–062UT-350 from Micro-Measurements, NC. The passive strain at the edge of the specimen ( $\epsilon_3$ ) for deter-



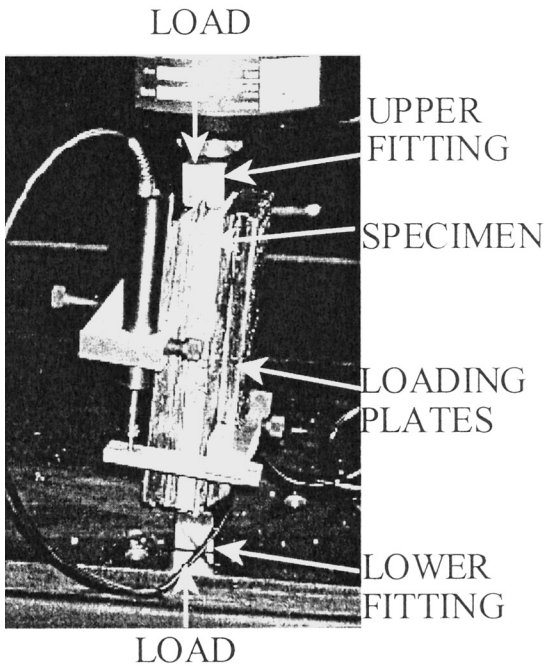


FIG. 4. Setup for the determination of  $G_{13}$ .

mination of  $\nu_{13}$  was simultaneously measured with a uni-axial strain gauge EA-06-031EC-350 from the same company glued exactly at the same position on the edge of the specimen (Fig. 5). A single set of six specimens per density level was used. The same specimens were equilibrated consecutively at the three relative humidity (RH) levels and tested in the first third of the elastic zone as done by Tang and Lee (1999). The Pois-

son's ratios were calculated in terms of the ratio of passive to active strain, i.e.  $\nu_{12} = -\epsilon_2/\epsilon_1$ ,  $\nu_{13} = -\epsilon_3/\epsilon_1$  (Bodig and Jayne 1993) corresponding to the load at which the test was interrupted. The load applied did not exceed the first third of the elastic zone. The MDF surface porosity is higher than that of solid wood and much higher than that of metals and plastics for which strain gauges are designed. To compensate for this porosity, the strain gauges were attached to the specimens with slow-hardening epoxy adhesive. The possible effect of this adhesive on the results was assessed by comparing  $E_1$  of specimens with surface covered with resin to  $E_1$  of regular specimens. The results did not show a significant difference between  $E_1$  of the two types of specimens, which led to the conclusion that the effect of epoxy resin could safely be disregarded.

#### RESULTS AND DISCUSSION

The test results are summarized in Table 1. The values of some mechanical properties (e.g.  $E_1$ ) obtained in the current work are somehow lower than some values found in the literature (e.g. Suchsland et al. 1978). It needs to be considered that the literature data are based on average density of panels with profile, where density of the surface layer is much higher (usually in excess of  $1000 \text{ kg/m}^3$ ), while the panels used in this research did not have a density profile.

##### *Test of isotropy in the 1–2 plane*

Because of the laboratory method of forming described above, there was no reason for the panels to experience anisotropy in the 1–2 plane. Still, half of the specimens for tests in the 1–2 plane were obtained parallel and the other half perpendicular to the 1-axis. A limited test on plane isotropy was conducted as described below. Analysis of variance (ANOVA) was performed on the  $E_1$  data using the SAS GLM procedure considering the impact of the nominal M, (3 levels), density (3 levels) and orientation (2 levels) of the  $E_1$  specimens (Table 2). The effects of nominal density, nominal M and the interac-

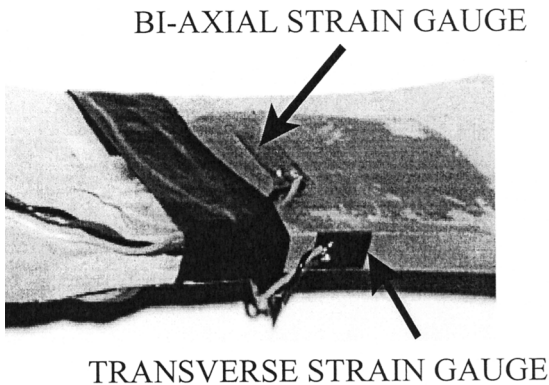


FIG. 5. Setup for the determination of  $\nu_{12}$  and  $\nu_{13}$ .

TABLE 1. Summary of results for mechanical properties.

Nominal density (kg/m <sup>3</sup> )	Nominal M (%)	Statistic	Actual density at 50% RH of E <sub>1</sub> specimens (kg/m <sup>3</sup> )	Actual M at 50% RH of E <sub>1</sub> specimens (%)	E <sub>1</sub> (MPa)	$\nu_{12}$	$\nu_{13}$	Actual density at 50% RH of E <sub>3</sub> specimens (kg/m <sup>3</sup> )	E <sub>3</sub> (MPa)	Actual density at 50% RH of G <sub>13</sub> specimens (kg/m <sup>3</sup> )	G <sub>13</sub> (MPa)
540	6.9	avg	531	7.0	728	0.31	0.43	541	18.7	536	54.6
		std	14.2	0.23	92.4	0.11	0.10	14.6	2.41	20.2	7.21
	10.0	avg	538	10.1	584	0.32	0.38	541	4.9	533	45.6
		std	13.6	0.29	87.7	0.10	0.10	21.7	0.67	11.2	5.06
	13.5	avg	539	13.6	447	0.29	0.33	539	3.9	535	46.9
		std	15.5	0.41	65.7	0.08	0.09	17.5	0.76	12.5	5.80
650	6.9	avg	667	7.0	1273	0.25	0.28	650	35.2	650	118.4
		std	13.1	0.17	104.9	0.07	0.08	16.6	3.02	22.3	5.14
	9.9	avg	653	10.0	1109	0.27	0.24	648	18.9	653	73.1
		std	16.5	0.28	81.6	0.12	0.06	21.3	1.79	25.6	3.70
	13.3	avg	642	13.4	970	0.29	0.22	651	10.6	652	48.7
		std	17.7	0.37	92.1	0.11	0.11	20.5	1.95	19.5	3.84
800	6.9	avg	786	7.0	2226	0.25	0.32	775	59.9	788	135.7
		std	25.7	0.26	91.1	0.09	0.07	22.8	4.55	27.4	3.81
	9.5	avg	788	9.6	1868	0.26	0.26	781	41.9	793	92.0
		std	26.2	0.32	81.8	0.10	0.12	21.1	3.37	20.4	4.60
	12.5	avg	789	12.5	1521	0.26	0.21	789	12.9	788	51.6
		std	24.8	0.41	99.8	0.04	0.08	14.9	2.43	21.6	5.02

TABLE 2. Results of analysis of variance for the impact of nominal density, nominal M, and orientation on  $E_1$ .

Source	DF	F-value	Pr>F
Model	2	320.81	<0.0001
Error	21		
orient	1	2.63	0.1105
nom_den	2	2344.99	<0.0001
nom_M	2	312.45	<0.0001
orient*nom_den	2	1.71	0.1905
orient*nom_M	2	0.68	0.5103
nom_M*nom_den	4	32.72	<0.0001
orient*nom_M*nom_den	4	0.15	0.9623

tion between nominal density and nominal M on  $E_1$  were significant. The effect of orientation and the interaction between orientation and the other factors were not significant. The results for  $E_1$  led to the conclusion that for laboratory MDF panels, there is no significant difference between the tensile moduli in axis 1 versus axis 2.

#### *Effect of density and M on $E_1$ , $E_3$ , $G_{13}$ , $\nu_{12}$ and $\nu_{13}$*

The results of the analysis of variance for the impact of nominal density and nominal M on the panel mechanical properties are presented in Table 3. The ANOVA was performed by comparing the properties for the specimens grouped under the three nominal density levels and three nominal M-levels. The F-values obtained for the ANOVA (Table 3) showed significant differences among the three density and M-levels for  $E_1$ ,  $E_3$ , and  $G_{13}$ . For  $\nu_{13}$  there were significant differences between two out of the three density and M-levels. For  $\nu_{12}$  there were no significant differences among the density and M-levels. Since the significance of difference for the Poisson's ratios is lower, and the variability of data is higher, they are not included in the further statistical analysis and in the following tables and graphs.

A Duncan's multiple range test on the means performed on the nominal density and M-level, established that the means obtained for  $E_1$ ,  $E_3$ , and  $G_{13}$  for all density and M-levels were significantly different.

Regression analysis between  $E_1$ ,  $E_3$ , and  $G_{13}$  and the actual density of the same specimens as

above (Table 4) sliced by nominal M groups also showed significant models. Wherever the quadratic terms were not significant, linear regression models were used. The coefficients of determination were high ( $R^2 \geq 0.87$ ) for all M-levels except for the case of  $G_{13}$  at an M-value of 13.1 % ( $R^2=0.22$ ). As seen in Fig. 6,  $E_1$ ,  $E_3$ , and  $G_{13}$  increase when the actual specimen density increases. At any density level, the panels conditioned to 6.9 % nominal M presented the highest mechanical properties and the panels conditioned to 13.1 % M presented the lowest mechanical properties. The ANOVA results based on nominal M (Table 3) suggested also a negative effect of M on the mechanical properties. These results are in agreement with the literature (e.g. Watkinson and Gosliga (1989) and Boëhme (1980) for  $E_1$  in MDF, Halligan and Schniewind (1974), and Lee and Biblis (1976) for IB strength in particleboard and Dong et al. (1992) and Schulte and Frühvald (1996) for  $G_{13}$  in particleboard and MDF).

The destructive nature of the tests used to determine  $E_3$  and  $G_{13}$  did not allow measuring the actual specimen M. For this reason, regression analysis was performed only for the effect of specimen M on  $E_1$ . The regression analysis by nominal density groups showed significant linear models between  $E_1$  and actual M (Table 5) with  $R^2$  between 0.63 and 0.86. The negative effect of M on  $E_1$  is illustrated in Fig. 7. The figure also shows that the higher the nominal density, the higher is  $E_1$ . As in the case of relations with density the models for  $\nu_{12}$  and  $\nu_{13}$  were not significant. The variability in the data for the Pois-



TABLE 3. Results of analysis of variance for the impact of nominal density and nominal M on  $E_1$ ,  $E_3$ , and  $G_{13}$

Source	E <sub>1</sub>			V <sub>12</sub>			V <sub>13</sub>			E <sub>3</sub>			G <sub>13</sub>		
	DF	F-value	Pr>F	DF	F-value	Pr>F	DF	F-value	Pr>F	DF	F-value	Pr>F	DF	F-value	Pr>F
Model	8	356.24	<.0001	8	0.51	0.0841	8	3.95	0.0013	8	422.86	<.0001	8	364.16	<.0001
Error	63	—	—	45	—	—	45	—	—	63	—	—	63	—	—
nominal_M	2	139.05	<.0001	2	0.08	0.9193	2	4.09	0.0239	2	741.82	<.0001	2	701.62	<.0001
nominal_density	2	1257.31	<.0001	2	1.69	0.9193	2	11.47	<.0001	2	756.69	<.0001	2	488.97	<.0001
nominal_M*nominal_density	4	14.29	<.0001	4	0.14	0.9678	4	0.13	0.9703	4	96.47	<.0001	4	133.02	<.0001
Nominal M	Duncan grouping by nominal M														
6.9	A			A			A			A			A		
9.8	B			A			BA			B			B		
13.1	C			A			B			C			C		
Nominal density	Duncan grouping by nominal density														
540	A			A			A			A			A		
650	B			A			B			B			B		
800	C			A			B			C			C		

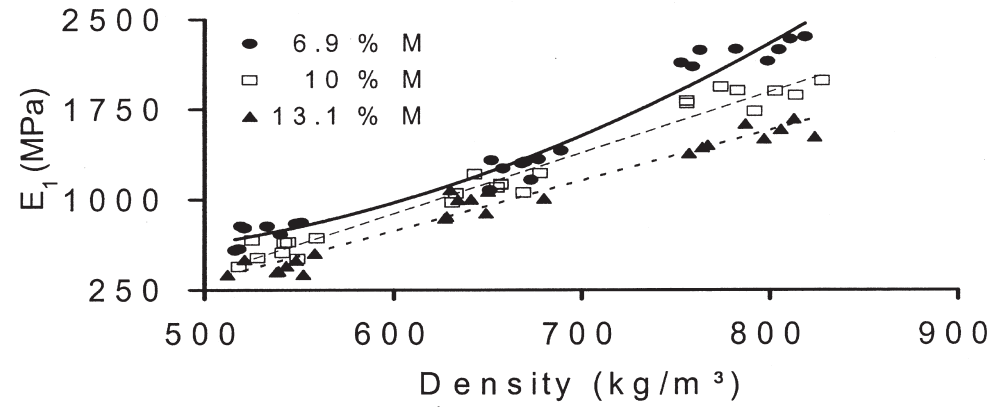
son's ratios was relatively high (standard deviation varying between 0.04 and 0.11, Table 1) although well in the range observed by Bulleit (1985) and only slightly higher than that reported by Moarcas and Irle (1999), the variability may partly explain the lack of relations between Poisson's ratios and both density and M. Since  $E_1 = E_2$ , and also as it will be discussed later  $E_1$  and  $E_3$  are affected by density and M at the same rate,  $\nu_{12}$  and  $\nu_{13}$  should not be affected by density or M change.

A complete illustration of the mechanical properties for all densities and panel types is given in Fig. 8. It can be observed that  $E_1$ ,  $E_3$ , and  $G_{13}$  increase when density increases;  $E_1$  is much higher than  $G_{13}$ , which in turn is higher than  $E_3$  at each nominal density level.

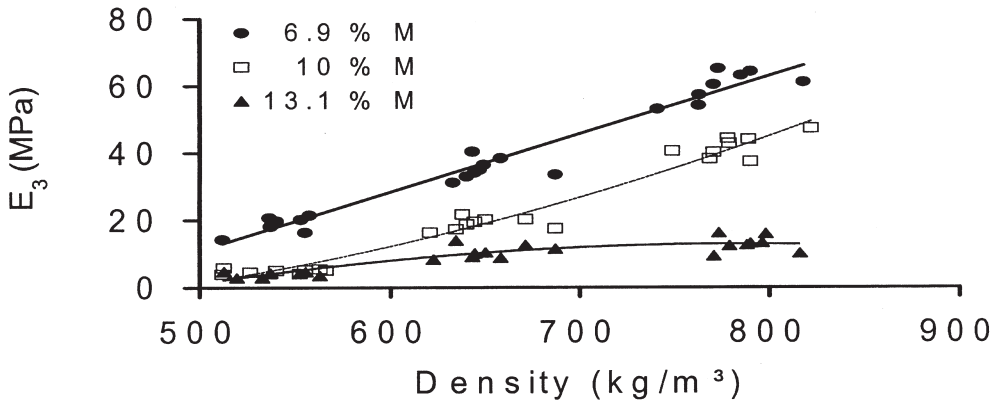
*Comparison of rates of increase of the mechanical properties*

The SAS REG (STB) procedure was used to obtain standardized regression coefficients between the mechanical properties and density. The standardized regression coefficients are identical to Pearson's correlation coefficients (r) between the same arrays of data. A comparison between each two of the standardized regression coefficients was performed according to a procedure described by Steiger (1980). The null hypothesis of equality between the coefficients is rejected with a probability of 95 % when the corresponding p-value is lower than 0.05. When the null hypothesis is rejected, the higher the standardized regression coefficient, the faster the property increases with density. The standardized regression coefficients and their grouping are summarized in Table 6.

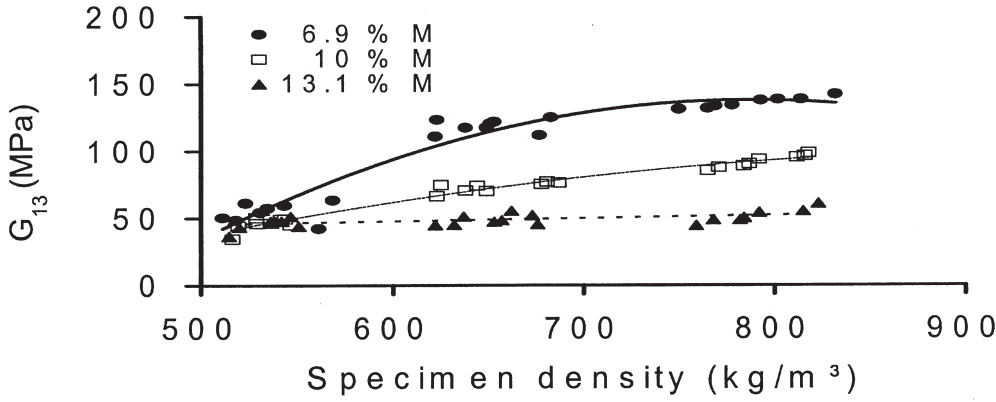
It can be observed that the strongest effect of density is on  $E_1$ ,  $E_3$ , and  $G_{13}$  (Table 6). The Poisson's ratios of  $\nu_{12}$  and  $\nu_{13}$  show negative standardized regression coefficients with density significantly lower than those for  $E_1$ ,  $E_3$ , and  $G_{13}$ . These relations can help explain some trends in complex phenomena such as warping, on which various properties may have opposite effects, while affected by density at different levels.



(a)



(b)



(c)

FIG. 6. Effect of actual specimen density and moisture content on: (a)  $E_1$ , (b)  $E_3$  and (c)  $G_{13}$ .

TABLE 4. Results of regression analysis between actual specimen density and  $E_1$ ,  $E_3$ , and  $G_{13}$ .

Source	$E_1$			$E_3$			$G_{13}$		
	DF	F-value	Pr>F	DF	F-value	Pr>F	DF	F-value	Pr>F
Model	2	310.49	<.0001	1	548.97	<.0001	2	131.37	<.0001
Error	21	—	—	22	—	—	21	—	—
ac_dens	1	607.05	<.0001	1	548.97	<.0001	1	235.13	<.0001
6.9 ac_dens*ac_dens	1	13.94	0.0012		—	—	1	27.61	<.0001
Regression equation	$E_1 = 2074.4 - 8.15ac\_dens + 0.01ac\_dens^2$			$E_3 = -75.79 + 0.17ac\_dens$			$G_{13} = -641.2 + 1.98ac\_dens - 0.001ac\_dens^2$		
R <sup>2</sup>	0.97			0.96			0.93		
Model	1	703.41	<.0001	2	287.92	<.0001	2	395.76	<.0001
Error	22	—	—	21	—	—	21	—	—
ac_dens	1	703.41	<.0001	1	570.67	<.0001	1	777.74	<.0001
ac_dens*ac_dens	—	n.s.	n.s.	1	5.18	0.0335	1	13.77	0.0013
Regression equation	$E_1 = -2146.3 + 5.05ac\_dens$			$E_3 = 1.66 - 0.09ac\_dens - 1.8 \times 10^{-4}ac\_dens^2$			$G_{13} = -175.92 + 0.57ac\_dens - 0.0003ac\_dens^2$		
R <sup>2</sup>	0.97			0.96			0.97		
Model	1	558.5	<.0001	2	44.93	<.0001	1	6.38	0.0192
Error	22	—	—	21	—	—	22	—	—
ac_dens	1	558.5	<.0001	1	81.44	0.0026	1	6.38	0.0192
13.1 ac_dens*ac_dens	—	n.s.	n.s.	1	8.42	0.0085		n.s.	n.s.
Regression equation	$E_1 = -1772.9 + 4.19ac\_dens$			$E_3 = -76.5 + 0.23ac\_dens - 1.5 \times 10^{-4}ac\_dens^2$			$G_{13} = 34.1 + 0.022ac\_dens$		
R <sup>2</sup>	0.96			0.87			0.22		

TABLE 5. Regression analysis between actual  $M$  and  $E_1$ , by density level.

Nominal Density		540			650			800		
Source	DF	F-value	Pr>F	DF	F-value	Pr>F	DF	F-value	Pr>F	
Model	1	39.67	<.0001	1	37.74	<.0001	1	136.49	<.0001	
	ac_M	1	39.67	<.0001	1	37.74	<.0001	1	136.49	<.0001
Regression equation		E <sub>1</sub> = 1006.4– 41.04ac_M			E <sub>1</sub> = 1580.3– 45.84ac_M			E <sub>1</sub> = 3064.5– 123.26ac_M		
R <sup>2</sup>		0.64			0.63			0.86		

CONCLUSIONS

The purpose of this study was to determine the impact of density and moisture content on  $E_1$ ,  $\nu_{12}$ ,  $\nu_{13}$ ,  $E_3$ , and  $G_{13}$  for MDF. The results show that for laboratory MDF panels there is no significant difference between mechanical properties measured in the panel plane. The moduli  $E_1$ ,  $E_3$  and  $G_{13}$  increase with nominal density at each M-level and decrease with an increase of mois-

ture content at each nominal density. The effect of density and moisture content on Poisson's ratios is not significant. The strongest effect of density is on  $E_1$ ,  $E_3$  and  $G_{13}$ .

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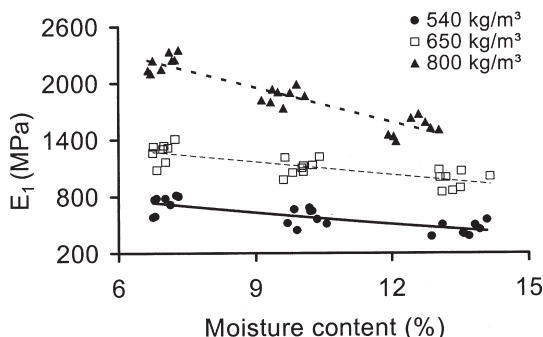


FIG. 7. Effect of actual specimen moisture content and nominal density on  $E_1$ .

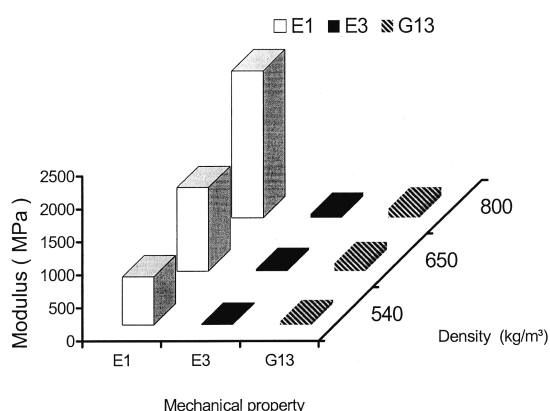


FIG. 8. Summary of the effect of nominal density and property type on the level of mechanical properties.

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TABLE 6. Effect of density on the mechanical properties expressed by standardized regression coefficients.

	Standardized Regression Coefficient
$E_1$	0.97
$E_3$	0.97
$G_{13}$	0.91
$v_{12}$	−0.26
$v_{13}$	−0.41

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