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 ν_{12} and ν_{13}. The relation of all parameters with density was determined from MDF panels without density profile with average density levels of 540 kg/m³, 650 kg/m³ and 800 kg/m. The relation with moisture content was determined from specimens conditioned to 50 % RH, 65 % RH and 80 % RH. Panel E_1, E_3 and G_{13} increased with density increase and decreased with M-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 M on the Poisson's ratios was not significant.

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

INTRODUCTION

The mechanical properties and the dimensions of medium density fiberboard (MDF) are strongly affected by moisture content (e.g. Chow, 1976, Halligan and Schniewind, 1974, Dong *et al*, 1992). The effect of a moisture content (M) change on panel flatness is difficult to predict due to 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. 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 (ΔM) can be expressed as follows if the principal material directions coincide with the principal directions of the coordinate system used (Figure 1):

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{Bmatrix} = \begin{bmatrix} \dfrac{1-\nu_{23}\nu_{32}}{E_2 E_3 S} & \dfrac{\nu_{21}+\nu_{23}\nu_{31}}{E_2 E_3 S} & \dfrac{\nu_{31}+\nu_{21}\nu_{32}}{E_2 E_3 S} & 0 & 0 & 0 \\ \dfrac{\nu_{21}+\nu_{23}\nu_{31}}{E_2 E_3 S} & \dfrac{1-\nu_{31}\nu_{13}}{E_1 E_3 S} & \dfrac{\nu_{23}+\nu_{21}\nu_{13}}{E_1 E_2 S} & 0 & 0 & 0 \\ \dfrac{\nu_{31}+\nu_{21}\nu_{32}}{E_2 E_3 S} & \dfrac{\nu_{23}+\nu_{21}\nu_{13}}{E_1 E_2 S} & \dfrac{1-\nu_{21}\nu_{12}}{E_1 E_2 S} & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & G_{13} & 0 \\ 0 & 0 & 0 & 0 & 0 & G_{12} \end{bmatrix} \left(\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_{23} \\ \varepsilon_{13} \\ \varepsilon_{12} \end{Bmatrix} - \begin{Bmatrix} \beta_1 \Delta M \\ \beta_2 \Delta M \\ \beta_3 \Delta M \\ 0 \\ 0 \\ 0 \end{Bmatrix} \right) \qquad (1)$$

with

$$S = \frac{1}{E_1 E_2 E_3}\left(1 - 2\nu_{21}\nu_{32}\nu_{13} - \nu_{13}\nu_{31} - \nu_{23}\nu_{32} - \nu_{12}\nu_{21}\right) \qquad (2)$$

Where: σ_{ij}=stress components vector;

ε_{ij}= strain components vector;

β_i=shrinkage/swelling expansion coefficient vector ($\%^{-1}$);

ΔM=moisture content change (%);

E_i=moduli of elasticity (Pa);

G_{ij}= shear moduli (Pa); ν_{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 ν_{12} as follows:

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

Consequently, seven independent parameters need to be determined experimentally as a function of density and M: E_1, E_3, ν_{12}, ν_{13}, G_{13}, β_1 and β_3. There is limited literature data 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 is 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) increase with density-increase (e.g. Boehme, 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 is 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; Boheme, 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 Frühwald (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 Frühwald (1996) and Wang et al. (1999) observed that when density increased so did G_{13}.

Poisson's ratios, ν_{12} and ν_{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 ν_{12} and for ν_{13} in the range of 0.3. No other data on ν_{13} were found in the literature. Other results published for ν_{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}, ν_{12} and ν_{13} as a function of density and moisture content ate 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 x 540 kg/m^3, 13 x 650 kg/m^3, 13 x 800 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 across the thickness.

Mechanical Tests

All mechanical tests were accomplished with a 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 (Figure 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 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 a 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 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 (Figure 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 (ν_{12} and ν_{13}) were obtained from the setup used for the determination of E_1 as described above. The active (ε_1) and the passive (ε_2) strains in the plane were recorded by using perpendicular grid type bi-axial strain gauges CEA-06-062UT-350 from Micro-Measurements, NC, USA. The passive strain at the edge of the specimen (ε_3) for determination of ν_{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 (Figure 5). A single set of six specimens per density level was used. The same specimens were equilibrated consecutively at the three RH levels and tested in the first third of the elastic zone as done by Tang and Lee (1999). The Poisson's ratios were calculated in terms of the ratio of passive to active strain, i.e. $\nu_{12} = -\varepsilon_2/\varepsilon_1$, $\nu_{13} = -\varepsilon_3/\varepsilon_1$ (Bodig and Jayne 1993) corresponding to the load at which the test was interrupted. 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 lead to the conclusion that the effect of epoxy resin could safely be disregarded.

RESULTS AND DISCUSSION

The results from the tests 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 is based on average density of panels with profile, where density of the surface layer is much higher (usually in excess of 1000 kg/m^3), while the panels used in this research did not have a density profile.

Test of isotropy in the 1-2 plane

Due to 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 interaction 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}, ν_{12} and ν_{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 ν_{13} there were significant differences between two out of the three density and M-levels. For ν_{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 the 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 a 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 (1990) and Boheme (1980) for E_l in MDF, Halligan and Schniewind (1974) and Lee and Biblis (1976) for IB strength in particleboard and Dong et al. (1992) and Schulte and Frühewald (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_l and actual M (Table 5) with R^2 between 0.63 and 0.86. The negative effect of M on E_l is illustrated in Figure 7. The figure also shows that the higher the nominal density, the higher is E_l. As in the case of relations with density the models for ν_{12} and ν_{13} were not significant. The variability in the data for the Poisson'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 $E_l = E_2$, and also as it will be discussed later E_l and E_3 are affected by density and M at the same rate, ν_{12} and ν_{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 Figure 8. It can be observed that E_1, E_3 and G_{13} increase when density increases; E_l 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 ν_{12} and ν_{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.

CONCLUSIONS

The purpose of this study was to determine the impact of density and moisture content on E_1, ν_{12}, ν_{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 an increase in moisture content. At each nominal density and decrease with M-increase. At each nominal density level the values of E_1 are much higher than the values of G_{13}, which in turn are higher than the values of E_3. 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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Legends for Tables

Table 1. Summary of results for mechanical properties

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

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

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

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

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

Nominal Density	Nominal M	Statistic	Actual Density at 50 % RH of E_1 specimens	Actual M at 50 % RH of E_1 specimens	E_1	ν_{12}	ν_{13}	Actual Density at 50 % RH of E_3 specimens	E_3	Actual Density at 50 % RH of G_{13} specimens	G_{13}
(kg/m³)	(%)	-	(kg/m³)	(%)	(MPa)	-	-	(kg/m³)	(MPa)	(kg/m³)	(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

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

Source	E_1			ν_{12}			ν_{13}			E_3			G_{13}		
	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	0.196	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		

Source		E_1			E_3			G_{13}		
		DF	F-value	Pr>F	DF	F-value	Pr>F	DF	F-value	Pr>F
6.9	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
	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^2	0.97			0.96			0.93		
10.0	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	$E_1 = -2146.3 + 5.05ac\_dens$			$E_3 = 1.66 - 0.09ac\_dens - 1.8*10^{-4}ac\_dens^2$			$G_{13} = -175.92 + 0.57ac\_dens - 0.0003ac\_dens^2$		
	R^2	0.97			0.96			0.97		
13.1	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
	ac_dens*ac_dens	-	n.s.	n.s.	1	8.42	0.0085		n.s.	n.s.
	Regression equation	$E_1 = -1772.9 + 4.19ac\_dens$			$E_3 = -76.5 + 0.23ac\_dens - 1.5*10^{-4}ac\_dens^2$			$G_{13} = 34.1 + 0.022ac\_dens$		
	R^2	0.96			0.87			0.22		

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_1 =1006.4-41.04ac_M			E_1 =1580.3-45.84ac_M			E_1 =3064.5-123.26ac_M		
R^2	0.64			0.63			0.86		

	Standardized Regression Coefficient
E_1	0.97
E_3	0.97
G_{13}	0.91
ν_{12}	-0.26
ν_{13}	-0.41

Legends for Figures

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

Figure 2. Setup for determination of E_1.

Figure 3. Setup for determination of E_3.

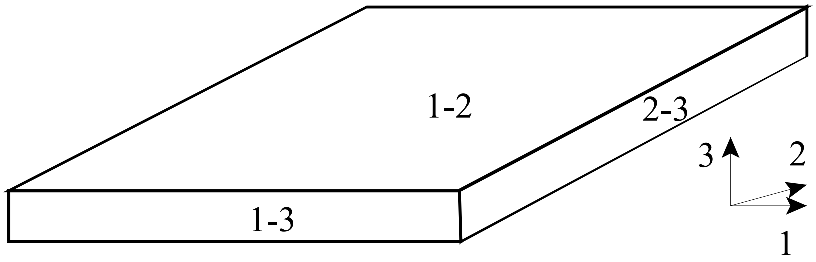
Figure 4. Setup for the determination of G_{13}.

Figure 5. Setup for the determination of ν_{12} and ν_{13}.

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

Figure 7. Effect of actual specimen moisture content on E_1.

Figure 8. Summary of the effect of nominal density and property type on the level of mechanical properties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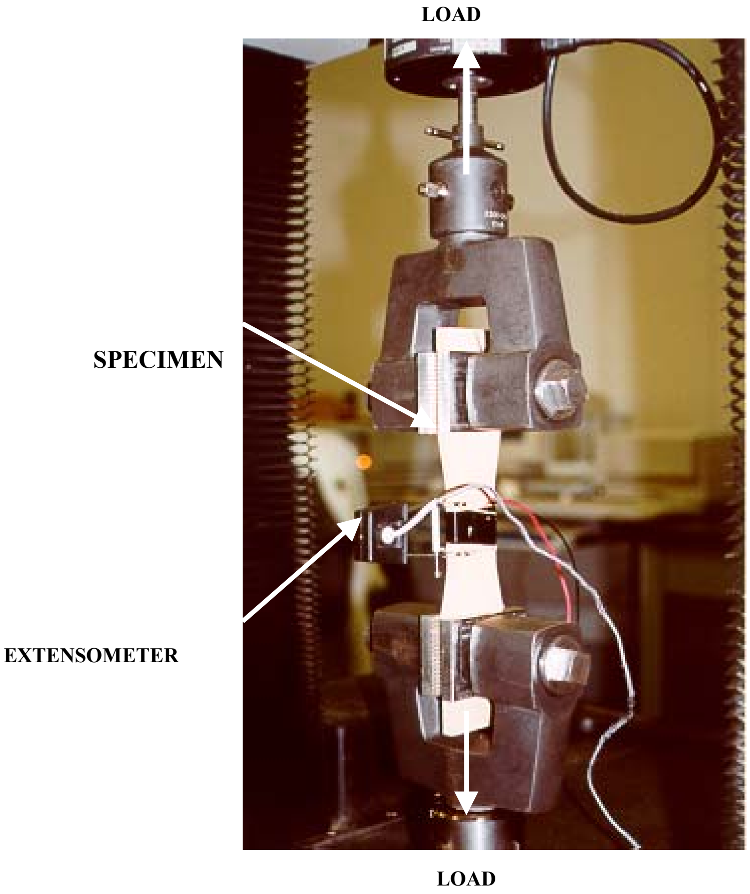
3
2
1-3
1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EXTENSOMETER
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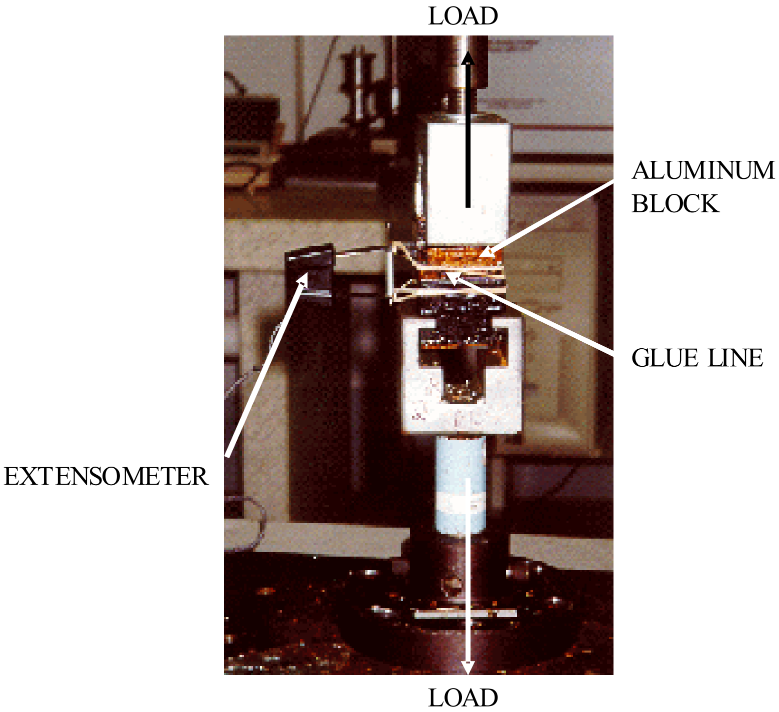
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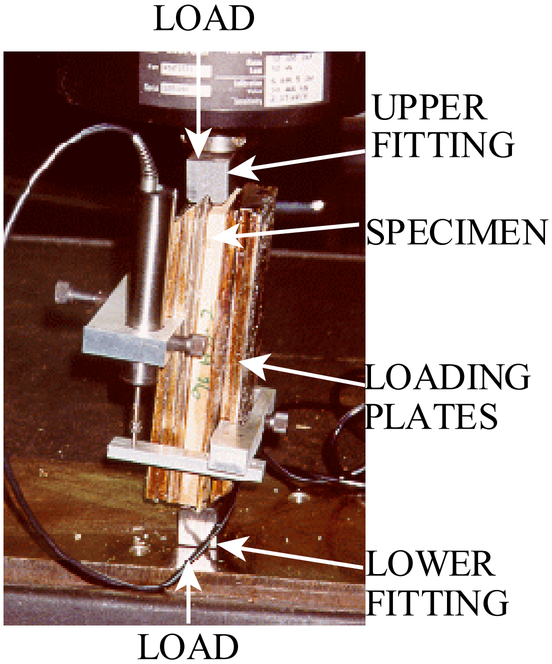
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LOWER
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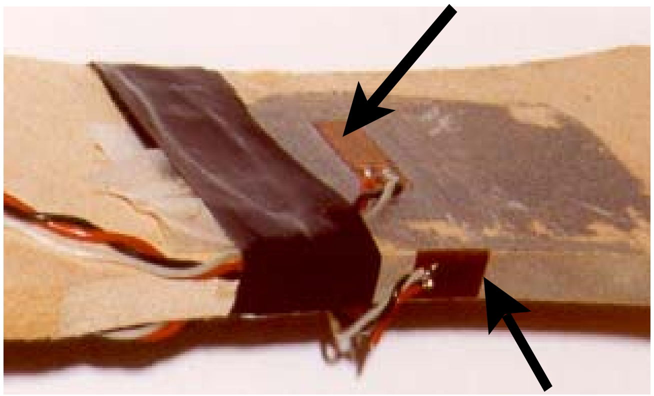
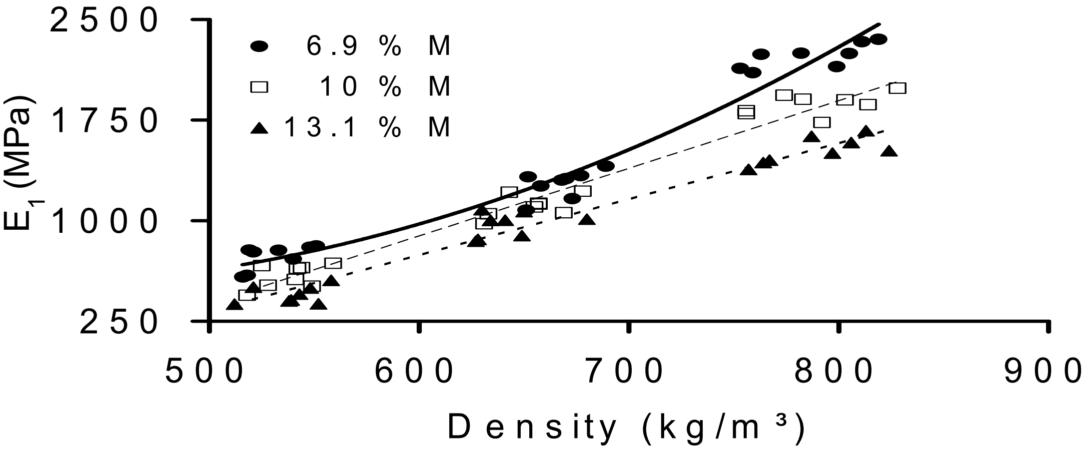
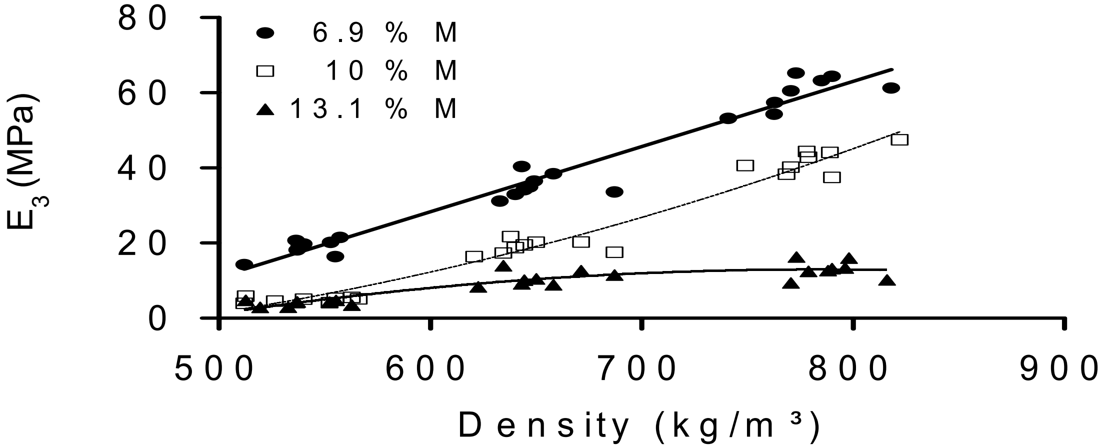
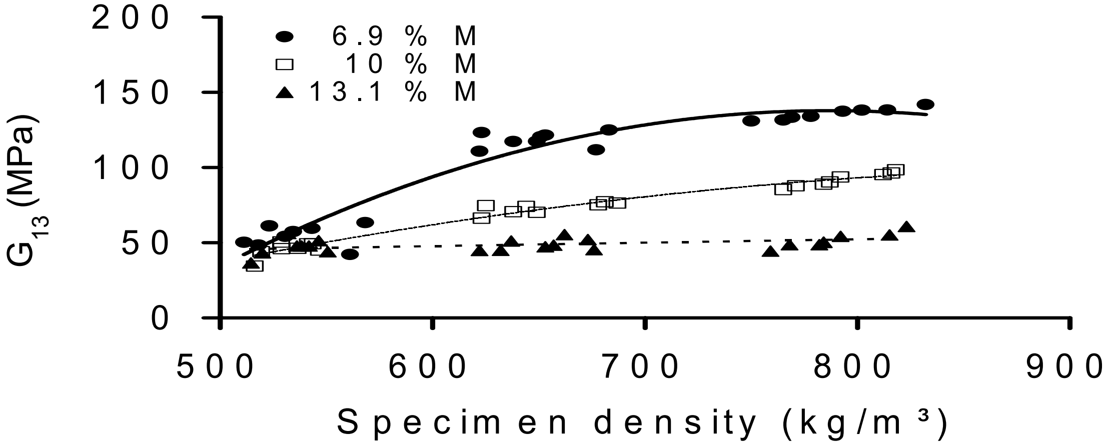

BI-AXIAL STRAIN GAUGE
TRANSVERSE STRAIN GAUGE


6.9 % M
10 % M
13.1 % M
2500
1750
1000
250
E_1 (MPa)
500
600
700
800
900
Density (kg/m³)

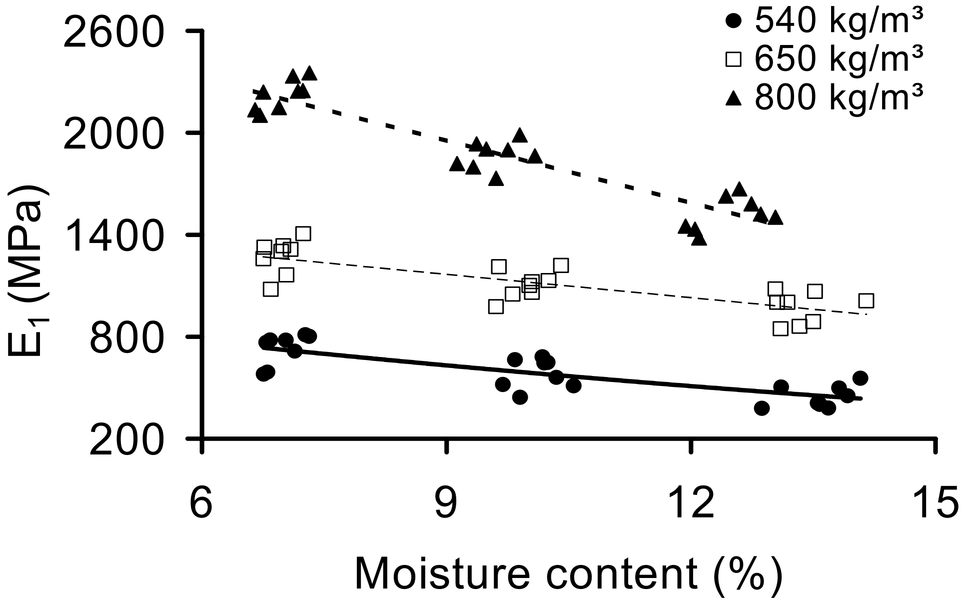
(a)

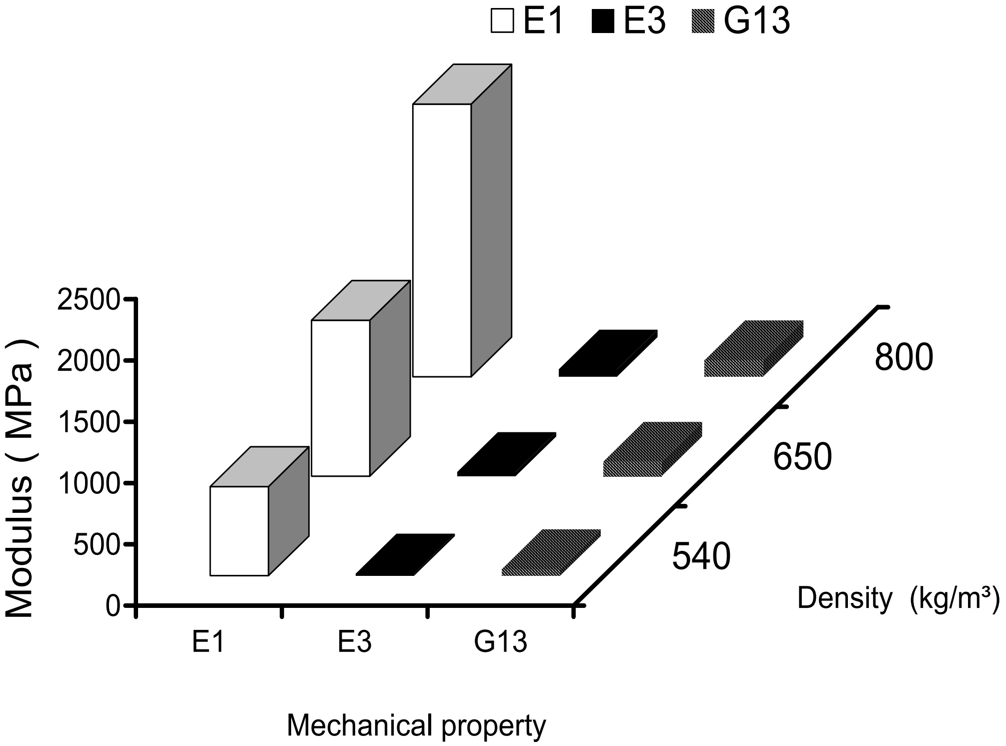

6.9 % M
10 % M
13.1 % M
80
60
40
20
0
E_3 (MPa)
500
600
700
800
900
Density (kg/m³)

(b)


6.9 % M
10 % M
13.1 % M
200
150
100
50
0
G_{13} (MPa)
500
600
700
800
900
Specimen density (kg/m³)

(c)


● 540 kg/m³
□ 650 kg/m³
▲ 800 kg/m³
2600
2000
1400
800
200
E_1 (MPa)
6
9
12
15
Moisture content (%)



☐ E1 ■ E3 ▨ G13
Modulus (MPa)
2500
2000
1500
1000
500
0
E1
E3
G13
Mechanical property
540
650
800
Density (kg/m³)