LINEAR EXPANSION AND THICKNESS SWELL OF MDF AS A FUNCTION OF PANEL DENSITY AND SORPTION STATE

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ABSTRACT

Experiments were conducted using ASTM standard methods to determine the medium density fiberboard (MDF) expansion properties and swelling characteristics as a function of panel density and sorption state. Specimens without density profile were produced by removing the surface layers of laboratory MDF panels. The results from the trials showed that for laboratory MDF, linear expansion is homogenous in panel plane. When specimen density increased, linear expansion, linear expansion coefficient, thickness shrinkage coefficient, linear contraction, and linear contraction coefficient increased. Thickness swell was higher than thickness shrinkage at any density level. Thickness swell coefficient was higher than thickness shrinkage coefficient for low density levels. The values of linear contraction and linear contraction coefficient (in desorption) were higher than the values of linear expansion and linear expansion coefficient (in adsorption). The values on thickness swell and thickness shrinkage were much higher than the values of linear expansion and linear expansion and linear contraction at any density level. The effect of density on linear expansion, linear expansion coefficient and linear contraction coefficient was significantly stronger than the effect of density on thickness swell, thickness swell coefficient and thickness shrinkage.

Keywords: MDF (medium density fiberboard), linear expansion, linear expansion coefficient, thickness swell, thickness swell coefficient, hysteresis.

INTRODUCTION

As solid wood and other wood-based composites, medium density fiberboard (MDF) is a hygroscopic material; therefore, its moisture content (M) depends on the relative humidity (RH) and temperature of the surrounding air. It is common knowledge that M and density affect MDF thickness swell and linear expansion (e.g. Chow 1976; Watkinson and Gosliga 1990). Consequently, when M is unevenly distributed through MDF thickness (M-profile), panel thickness swell and linear expansion vary accordingly, (Xu et al. 1996). The M-profile corresponds to the characteristic vertical distribution of density (density profile) and also affects the distribution of thickness swell (Xu and Winistorfer 1995) and linear expansion (Woodson 1975). For example, in MDF, the surface layers, although thinner, due to their higher compaction ratio, account for a more important portion of the overall thickness swell (Xu and Winistorfer 1995) compared to the core layer. The contribution of each panel layer on complex phenomena such as warp and its dynamics could be simulated with numerical methods such as the finite element method. To enable such simulations, the effects of MDF density and sorption state on the linear expansion and thickness swell at exposure to water in vapor phase (as opposed to immersion in liquid water) need to be characterized.

BACKGROUND

A hygromechanical model for warp simulation based on the equations of equilibrium has been presented in previous publications (Cloutier et al. 2001). For MDF, there are limited literature data available for the effects of panel density and sorption state (effect of adsorption versus desorption branch of the sorption isotherm) on the linear expansion and thickness swell at exposure to water in the vapor phase.

Determination of the expansion properties

According to ASTM D 1037 (ASTM 1999), for MDF the linear variation, or for simplicity the linear expansion (LE), between two equilibrium moisture contents (EMC), is calculated as percentage of the initial specimens' length. The hygroscopic strain is determined at $20 \pm 2°C$ as the percentage change of the initial length recorded at equilibrium, usually at 50% RH in adsorption and at 80% (or 90%) RH in desorption. In some studies, the linear variation is expressed in terms of LE change per 1% M change or linear expansion coefficient, LEC (Suchsland 1974). In desorption, corresponding notions would be linear contraction (LC) and linear contraction coefficient (LCC). In this study, we use the group term "expansion properties" for LE, LEC, LC, and LCC. In adsorption, the ASTM D 1037-99 procedure provides for two possible levels of final equilibration, either 80 or 90% RH. The 80% RH upper limit is more practical since when the 90% RH limit is used, wood composites may never reach equilibrium or the test could last for many months (Suchsland and Xu 1989).

In MDF, similarly to solid wood, the LE is explained by swelling in the cell walls (e.g., Xu and Suchsland 1991). Some authors (e.g., Suchsland and Xu 1989) consider LE to be a reversible phenomenon.

There is a contradiction in the literature concerning the effect of density on the expansion properties. Suchsland et al. (1978) and Xu and Suchsland (1997) for MDF, and Hiziroglu and Suchsland (1993) for particleboard did not find panel density to have an effect on LE. Most other researchers observed that when density increases, the expansion properties also increase (e.g., Woodson 1975 for MDF; Vital et al. 1980; Fujimoto et al. 1995; and Suzuki and Miyamoto 1998 for particleboard; Geimer 1982 for flakeboard).

Determination of swelling properties

The thickness variation induced by a change in M, also called thickness swell (TS), is the thickness variation between two EMC, calculated as percentage of the initial specimens thickness. This property has seldom been deter-

mined. A more popular evaluation has been immersion in water according to ASTM D 1037-99: Water Absorption and Thickness Swelling. The procedure can be modified for the determination of TS between two EMC levels (e.g., between 50 and 80% RH similarly to LE). Expressing the thickness variation as TS per 1% M change results in a thickness swelling coefficient, TSC. Similarly to expansion properties, the term "swelling properties" is introduced. In desorption, the corresponding concept to TS would be thickness shrinkage (TSh) and to TSC would be thickness shrinkage coefficient (TShC).

The size of the specimens specified in ASTM D 1037–99 can be altered, as done by Niemz and Poblete (1996), who used specimens with dimensions of 20 mm × 200 mm, or by Suzuki and Miyamoto (1998), who took measurements from the standard-size LE specimens.

We could not find any data on the effect of density on the swelling properties in MDF between two EMC conditions. A theoretical model of Xu and Winistorfer (1995) predicts that in MDF, the high-density regions in the density profile contribute twice as much to the total cumulative TS as compared to the low-density layers. This was experimentally confirmed. When immersed in water for 48 h, MDF specimens cut into 1.6-mm slices across the thickness experienced two times higher swelling in the surface layers as compared to the core layer (Xu and Winistorfer 1995). Although the thickness swelling was a time-dependent process, the authors had no doubt that there was a positive correlation of TS with layer density. For particleboard exposed to varying RH, Greubel and Paulitsch (1977) observed that when panel average density increased, so did TS. These two studies suggest that when specimen density increases, so do the swelling properties.

Objective

The objective of this research was to determine MDF expansion properties LE, LEC, LC, and LCC, and swelling properties TS, TSC, TSh, and TShC as a function of panel density and sorption state.

MATERIALS AND METHODS

Materials

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% M before resin blending. Commercial melamine urea-formaldehyde (MUF) resin was provided by Borden Canada.

The calculated quantities of the components were mixed in a laboratory rotary blender. The MUF 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. Catalyst was not used. 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 × 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 13 mm. Finally, the pressure was gradually reduced to zero and the press opened within approximately 15 to 20 s.

A total of 39 laboratory MDF panels, with a thickness of 12 mm, divided into three nominal density groups (13 × 540 kg/m^3, 13 × 650 kg/m^3, 13 × 800 kg/m^3), were produced. Each panel was edge-trimmed (approximately 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 to 8 mm by sanding. Thus panels with a flat profile (without vertical den-

sity variation) with dimensions 540 mm × 540 mm were obtained. This allowed a study of the effect of density on panel properties while eliminating the effect of the 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.

Expansion properties.—The expansion properties (LE, LEC, LC, and LCC) were determined according to ASTM D 1037-99: Linear Variation with Change in Moisture Content. The change in length was monitored at 20°C from 50% to 80% RH in adsorption and then from 80% to 50% RH in desorption on the same specimens. The expansion properties were calculated as follows:

$$LE = \frac{\left(L_{80} - L_{50\_initial}\right) \times 100}{L_{50\_initial}} \quad (1)$$

$$LEC = \frac{LE}{\Delta M} \quad (2)$$

$$LC = \frac{\left(L_{80} - L_{50\_final}\right) \times 100}{L_{80}} \quad (3)$$

$$LCC = \frac{LC}{\Delta M} \quad (4)$$

$$\Delta M = M_{80} - M_{50} \quad (5)$$

where: LE = linear expansion, %;
LEC = linear expansion coefficient, %/%;
LC = linear contraction, %;
LCC = linear contraction coefficient, %/%;
$L_{50\_initial}$ = initial specimen length after conditioning to 50 % RH before exposure to 80 % RH, m;
L_{80} = specimen length at equilibrium at 80 % RH, m;
L_{50_final} = final specimen length after re-conditioning to 50 % RH, m;
ΔM = moisture content increase (decrease), %;
M_{80} = moisture content at 80 % RH, %; M_{50} = moisture content at 50 % RH, %

Eight specimens were tested per density level. At each equilibrium level, in addition to the length, the mass of the specimens was also recorded. At the end of the test, the specimens were oven-dried, and M at each level of RH was determined according to ASTM D 1037-99. The standard LE test does not allow obtaining expansion data at intermediate M values. It would be useful in a future research to modify the test and to validate the linearity of the LE versus M relation.

Swelling properties.—For evaluation of TS, the LE specimens (8 specimens per density level group) were used. The specimen thicknesses at three points midway across the width of the specimens (Fig. 1) were measured with an accuracy of ± 0.3%. The thicknesses were recorded once equilibrium was reached at 50 and 80% RH and after reconditioning to 50% RH. The swelling properties were calculated as follows:

$$TS = \frac{\left(T_{80} - T_{50\_initial}\right) \times 100}{T_{50\_initial}} \quad (6)$$

$$TSC = \frac{TS}{\Delta M} \quad (7)$$

$$TSh = \frac{\left(T_{50\_final} - T_{80}\right) \times 100}{T_{80}} \quad (8)$$

$$TShC = \frac{TSh}{\Delta M} \quad (9)$$

where: TS = thickness swell, %;
TSC = thickness swell coefficient, %/%;
TSh = thickness shrinkage, %;
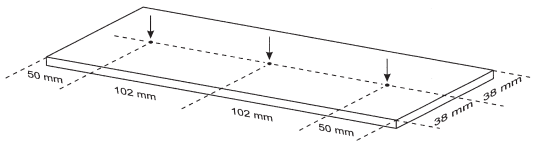TShC = thickness shrinkage coeffi-

FIG. 1. Positions for measuring thickness variations.

cient, %/%;

$T_{50\_initial}$ = initial specimen thickness after conditioning to 50 % RH before exposure to 80 % RH;

T_{80} = specimen thickness at equilibrium at 80 % RH;

T_{50_final} = final specimen thickness after re-conditioning to 50 % RH;

RESULTS AND DISCUSSION

The results obtained in this study are summarized in Table 1.

Test of isotropy in the panel 1-2 plane.—Due to the methodology used to form the mat (see above) there was no reason for the panels to exhibit anisotropy in the panel plane. In order to verify this assumption, four of the specimens prepared for tests in the panel plane were obtained parallel to one edge of the panel and the other four perpendicular to that direction. A test of isotropy in the plane regarding expansion properties was conducted as described below. An analysis of variance (ANOVA) was performed on the LE data using the SAS GLM procedure considering the impact of density (3 levels) and orientation (2 levels) of the LE specimens. The effect of nominal density on LE was significant (F-value of 13.77), while the effects of orientation (F-value of 0.36) and of nominal density combined with orientation (F-value of 1.09) were not significant. The results led to the conclusion that for MDF panels used in this research, there was no significant difference between LE obtained for two perpendicular directions in the panel plane.

Effect of density and initial M on TS, TSC, LE, LEC, TSh, TShC, LC and LCC.—The ANOVA results for the impact of nominal density on the panel expansion properties are presented in

TABLE 1. *Summary of results for swelling and expansion properties.*

Nominal density (kg/m³)	Statistic	Density at 50% RH (kg/m³)	Actual M at initial 50% RH (%)	Actual M at 80% RH (%)	Actual M at final 50% RH (%)	Thickness swell (TS) (%)	Thickness shrinkage (TSh) (%/%)*	Thickness swell coefficient (TShC) (%/%)*	Thickness shrinkage coefficient (TShC) (%/%)*	Linear expansion (LE) (%)	Linear contraction (LC) (%)	Linear expansion coefficient (LEC) (%/%)*	Linear contraction coefficient (LCC) (%/%)*
540	avg	535	6.8	14.2	9.4	3.8	2.6	0.74	0.54	0.13	0.16	0.017	0.034
	std	14	0.4	0.9	0.6	0.4	0.4	0.05	0.08	0.05	0.02	0.006	0.004
650	avg	665	6.9	13.5	9.4	3.6	2.6	0.77	0.62	0.15	0.20	0.023	0.048
	std	21	0.7	1.3	0.9	0.7	0.5	0.12	0.08	0.04	0.03	0.004	0.011
800	avg	790	6.8	13.2	9.9	4.3	3.1	0.84	0.95	0.23	0.25	0.036	0.077
	std	26	0.4	0.7	0.6	0.7	0.4	0.12	0.14	0.03	0.01	0.002	0.005

* % property change per % M-change

Table 2. The ANOVA was performed by comparing the properties for the specimens grouped under the three nominal density levels. The F-values showed a significant density effect for LE, LEC, TSh, TShC, LC, and LCC. For TS and TSC, there were no significant differences between the three density levels. A Duncan's multiple range test on the mean expansion coefficients obtained as a function of the nominal density showed that for LEC, LC, and LCC, the means for all density levels were significantly different. For LE, TSh, and TShC there were significant differences between the values at 540 kg/m^3, and the values at 650 kg/m^3 and 800 kg/m^3. The values at density levels 650 kg/m^3 and 800 kg/m^3 were not significantly different. The coefficients of determination were relatively high (R^2 between 0.60 and 0.77) except for the cases of TS, TSC, and TSh. This means that there is a strong effect of the actual specimen density on LE, LEC, TShC, LC, and LCC. The relations between density and the expansion and swelling properties are presented in Fig. 2. It can be observed that when density increases, all expansion and swelling properties increase. The trends were in agreement with the results published by Vital et al. (1980) and Fujimoto et al. (1995). Regression analysis between TS, TSC, LE, LEC, TSh, TShC, LC, and LCC and the actual density of the same specimens as above at nominal M of 6.9 % showed significant linear regression models for all properties but TS (Table 3). The regression analysis performed by density groups did not show significant models between TS, TSC, LE, LEC, TSh, TShC, LC, and LCC and actual specimen M (at initial equilibrium to 50 % RH). This leads to the conclusion that variability in M of MDF specimens at equilibrium in the beginning of the tests is not large enough to induce variability in the expansion coefficients.

Effect of sorption state on the expansion properties

Differences were observed between the expansion properties recorded in adsorption and desorption at the same density level (Table 1). The significance of difference between the corresponding properties in adsorption and desorption were validated with ANOVA (Table 4). The comparison between the expansion properties obtained in adsorption and desorption is facilitated by the linear regression curves (expansion properties versus density) included in Fig. 2. Thickness swell (adsorption) is higher than TSh (desorption) at any density level (Fig. 2a). Recalculated per 1 % M change, the TSC (adsorption) is higher than TShC (desorption) for lower density levels (Fig.2b). In wood and wood composites, the moisture adsorbed at high RH exposure is never entirely released when re-drying to lower RH levels (well-known hysteresis phenomenon, e.g., Siau 1995). The swelling hysteresis (the differences between TS and TSh) could be due to the progressive failure of bounds following panel swelling. The different slopes of TSC and TShC as a function of density may be attributed to a combined effect of two phenomena observed with MDF: the lower M-hysteresis at higher M-levels and the lower equilibrium M of panels with higher density (Ganev et al. 2003).

It is observed (Table 1 and Fig. 2c and d) that the LC (desorption) is approximately 20%

TABLE 2. *Analysis of variance for the impact of nominal density on TS, TSC, TSh, TShC, LE, LEC, LC, and LCC.*

Density level	TS F-value	TS Duncan	TSC F-value	TSC Duncan	TSh F-value	TSh Duncan	TShC F-value	TShC Duncan	LE F-value	LE Duncan	LEC F-value	LEC Duncan	LC F-value	LC Duncan	LCC F-value	LCC Duncan
540						A		A		A		A		A		A
650	2.4^{ns}		2.1^{ns}		4.9*	B	32.5**	B	13.6**	B	35.4**	B	41.5**	B	69.4**	B
800						B		B		B		C		C		C

^{ns} non significant
* significant at the 95% probability level
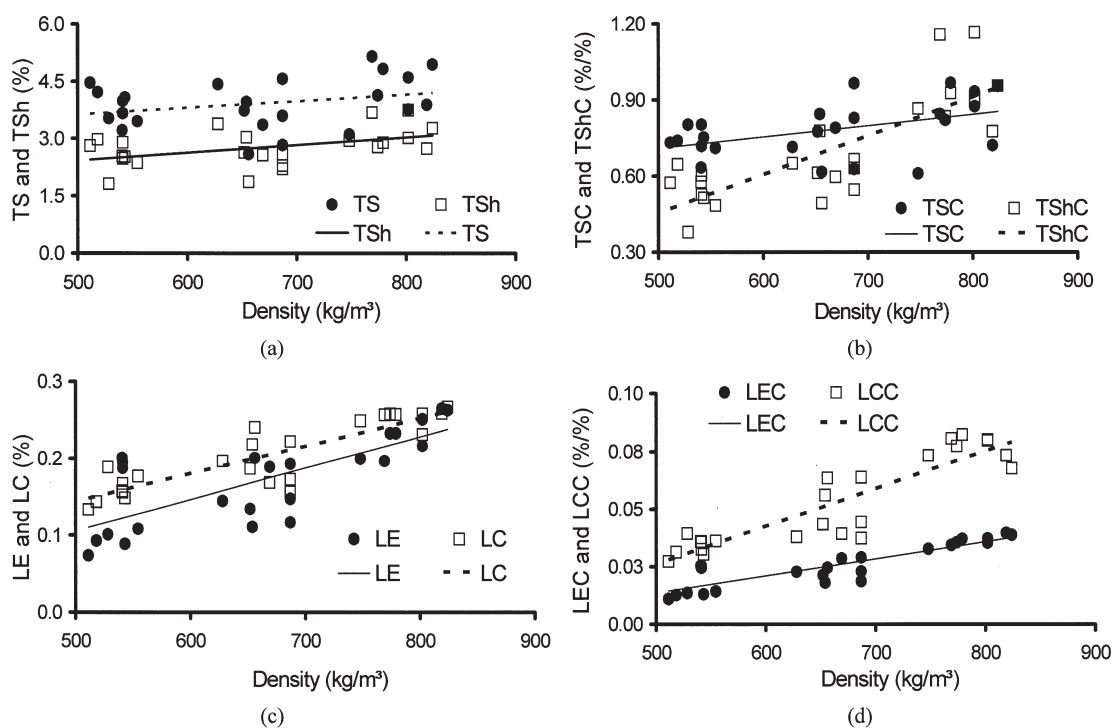** significant at the 99% probability level

FIG. 2. Effect of actual specimen density and sorption state on: (a) TS and TSh; (b) TSC and TShC; (c) LE and LC and (d) LEC and LCC.

higher than the LE (adsorption); the LCC (desorption) is at least 50 % higher than the LEC (adsorption) in the entire density range. It seems that the difference between LEC and LCC even increases with density. The M-hysteresis emphasizes the differences in the expansion properties in the panel plane because even though the specimens release less moisture in desorption, they contract more than they had expanded. These observations are supported by a study of Suchsland and Xu (1989). The authors observed a negative expansion hysteresis in MDF (the specimens become shorter upon re-drying). According to Suchsland and Xu (1989), this phenomenon is typical for all fiberboards (MDF and hardboard). Probably, for explanation of the phenomenon, a microscopic approach needs to be adopted: a methodology based on microscopy needs to be developed for monitoring of the alignment of the fibers and their configuration during the entire cycle of expansion and contrac-

tion. Also, trials based on multiple cycles may help clarify this phenomenon.

A complete illustration of the expansion properties for all densities and panel types is given in Fig. 3 (a) and (b). It suggests that:
- All expansion properties tend to increase when density increases;
- The values of TS and TSh are much higher than the values of LE and LC;
- The values of TSC and TShC are much higher than the values of LEC and LCC at any density level.

Comparison of the rates of increase of the expansion properties

The SAS REG (STB) procedure was performed to obtain standardized regression coefficients between the expansion properties and density. The standardized regression coefficients are identical to Pearson's correlation coefficients

TABLE 3.   *Results of regression analysis between actual specimen density and TS, TSC, TSh, TShC, LE, LEC, LC, and LCC.*

	TS			TSC			TSh			TShC		
Source	DF	F-value	Pr>F	DF	F-value	Pr>F	DF	F-value	Pr>F	DF	F-value	Pr>F
Model	1	3.08	0.0671	1	5.57	0.0276	1	5.47	0.0289	1	37.59	<.0001
Error	22	—	—	22	—	—	22	—	—	22	—	—
ac_dens	—	—	—	1	5.57	0.0276	1	5.47	0.0289	1	37.59	<.0001
Regression equation	n.s.			TSC = 0.49+ 0.0004ac_dens			TSh= 1.44+ 0.002ac_dens			TShC = 0.313+ 0.0015ac_dens		
R^2				0.20			0.20			0.63		
	LE			LEC			LC			LCC		
Source	DF	F-value	Pr>F	DF	F-value	Pr>F	DF	F-value	Pr>F	DF	F-value	Pr>F
Model	1	29.14	<.0001	1	72.47	<.0001	1	66.15	<.0001	1	91.84	<.0001
Error	22	—	—	22	—	—	22	—	—	22	—	—
ac_dens	1	29.14	<.0001	1	72.47	<.0001	1	66.15	<.0001	1	91.84	<.0001
Regression equation	LE = −0.099+ 0.0004ac_dens			LEC = −0.023+ $7.3*10^{-5}$ac_dens			LC = −0.037+ $3.6*10^{-4}$ac_dens			LCC = −0.056+ $1.6*10^{-4}$ac_dens		
R^2	0.6			0.77			0.75			0.75		

TABLE 4.   *Results of analysis of variance for effect of sorption state on the swelling and expansion properties.*

	TS vs TSh			TSC vs TShC			LE vs LR			LEC vs LCC		
Source	DF	F-value	Pr>F	DF	F-value	Pr>F	DF	F-value	Pr>F	DF	F-value	Pr>F
Model	5	14.36	<.0001	5	15.85	<.0001	5	18.33	<.0001	5	95.78	<.0001
Error	42	—	—	42	—	—	42	—	—	42	—	—
sorption_state	1	58.63	<.0001	1	6.84	0.0123	1	10.93	0.0019	1	234.59	<.0001
density	2	6.43	0.0037	2	26.4	<.0001	2	39.99	<.0001	2	105.81	<.0001
sorption*density	2	0.16	0.8489	2	9.8	0.0003	2	0.36	0.7032	2	16.35	<.0001

(r) between the same arrays of data (Steiger 1980). The null hypothesis of equality between the coefficients is rejected with probability of 95% when the corresponding p-value is lower than 0.05. In the case when the null hypothesis is rejected, the higher the standardized regression coefficient, the faster the property increases with density. These relations can help explain the effect of vertical density profile on warping, on which various properties may have opposite effects, while affected by density to different extents.

The standardized regression coefficients obtained for the linear regressions presented in Fig. 2 indicate that density has the strongest effect on LEC, LC, and LCC followed by LE and TShC. The TSC, TSh, and TS show a significantly lower standardized regression coefficient with density indicating that these properties will not increase as fast as the others when density increases.

CONCLUSIONS

The purpose of this study was to determine the MDF expansion properties LE, LEC, LC, and LCC, and swelling properties: TS, TSC, TSh, and TShC as a function of panel density and sorption state. The experiments were conducted using ASTM standard methods. The results show that for laboratory MDF, LE is homogenous in the panel plane. When specimen density increases, so do LE, LEC, TShC, LC, and LCC. Thickness swell is higher than thickness shrinkage at any density level. Thickness swell coefficient is higher than TShC for low density levels. The expansion properties are higher in desorption than in adsorption with LC approximately
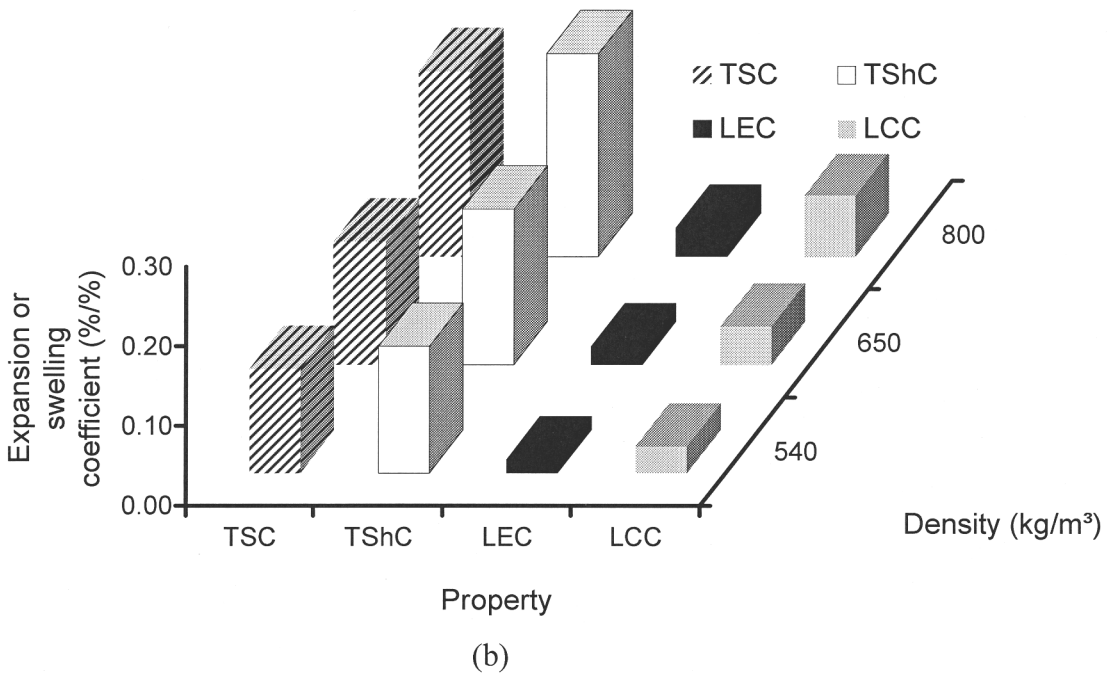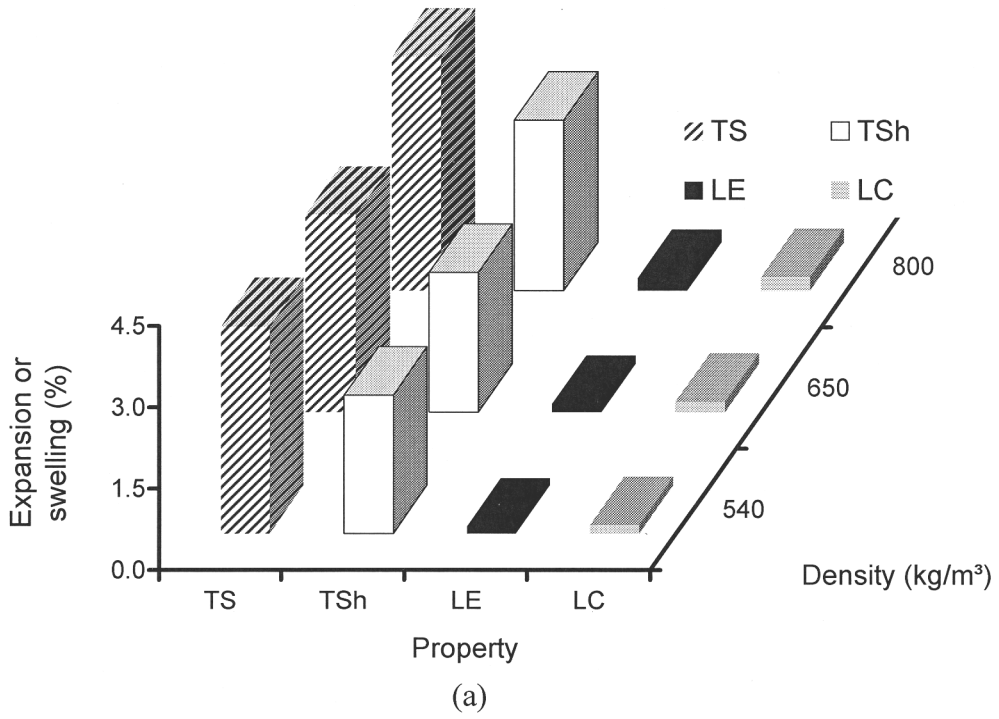
(a)

(b)

FIG. 3.   Summary of the effect of nominal density on the level of: (a) TS (STD = 0.28, TSh (STD = 0.45), LE (STD = 0.75) and LC (STD = 0.87); (b) TSC (STD = 0.47), TShC (STD= 0.79), LEC (STD = 0.88) and LCC (STD = 0.90).

20% higher than LE and LCC at least 50% higher than LEC. The values of TS and TSh are much higher than the values of LE and LC; the values of TSC and TShC are much higher than the values of LEC and LCC at any density level. The effect of density on LE, LEC, and LCC is significantly stronger than the effect of density on TS, TSC, and TSh.

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