IN-PLANE STABILITY OF ORIENTED STRANDBOARD: LAYER PROPERTIES IN RELATION TO PROCESSING VARIABLES

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ABSTRACT

Single-layer oriented strandboards (OSBs) were fabricated under a combination of three alignment levels, four densities and two resin contents. Flake orientation, density gradient across panel thickness, linear expansion (LE) and bending properties were measured. Flake orientation distribution was characterized with the von Mises distribution using mean flake angle and concentration parameter.

It was shown that the shape of the LE-moisture content change curve varied with alignment level and material direction. The variation was attributed to the difference in the controlling mechanism for LE in various panels. Total LE from oven-dry to water-soak condition, modulus of elasticity (MOE) and modulus of rupture (MOR) varied significantly with flake orientation distribution and density, but not resin content. LE, MOE and MOR were correlated with the concentration parameter, density, resin content and moisture content using a power form equation. The experimental data forms a database of layer properties for modeling three-layer, cross-laminated OSBs manufactured under hot pressing.

INTRODUCTION

Oriented strandboard (OSB) is a structural panel that consists of wood strands glued with an exterior-type, waterproof resin. The physical properties of the board are enhanced by layering and alignment of wood flakes. Based on current industry announcements, OSB capacity will reach 18.4 million m^3 in 1997, with production projected at 15.5 million m^3 [8]. As with most commodity products, competition has forced product and process optimization which reduces the margin for manufacturing errors.

OSB swells significantly when the product is exposed to high relative humidity (RH) conditions [10,11]. In addition to the well-recognized importance of thickness stability, in-plane swelling, known as linear expansion (LE), can be a significant factor in structural applications. This is so because the swelling can greatly affect the state of stress that exists in the material. The in-plane movements can cause high internal stresses due to the restraint offered by external fastening such as nails. These stresses may be large enough to cause buckled panels, pushed-out nails and separation of the panel from the structure [4,10].

The dimensional change is a direct result of complex interactions among different layers across panel thickness. Many processing parameters affect the dimensional change of a three-layer panel, the most important being flake orientation, shelling ratio (i.e. weight ratio between face layer and core layer), degree of bonding, flake geometry, density and density gradient. Variation in these variables among different products has led to a large variability of LE values in commercial OSBs marketed [10]. Efforts to reduce LE in these products require a quantitative understanding of the role each variable plays in controlling the in-plane movement.

Earlier work —

The study reported here represents the first part of a comprehensive study aimed at examining dimensional stability and durability of OSB. The objective of this work was to investigate to what extent in-plane stability of single-layer OSB is related to processing variables, namely, flake alignment level, density and resin content at various levels of moisture content (MC). Since the in-plane movement and strength properties are closely related, data on bending modulus of elasticity (MOE) and modulus of rupture (MOR) were also presented.

MATERIALS AND METHODS

Board Fabrication

Forty-four single layer OSB panels were manufactured (Table 1) in the USDA Forest Products Laboratory, Madison, Wisconsin. In brief, a number of Aspen logs with an average diameter of 45-cm were obtained at a local Wisconsin sawmill. The logs were band-sawn into 13-mm thick boards, which were ripped to eliminate bark and crosscut into 152-mm long blocks. These blocks were oriented with the grain direction parallel to the knives of a disk flaker and cut into flakes measuring 0.645-mm thick x 13-mm wide x 76-mm long. The flakes were then dried to about 5% MC and screened. The boards were pressed to a thickness of 12.7-mm in a cold press and were then heated under pressure until the core temperature passed 104 °C. This was done to eliminate vertical density gradient inside the boards [2]. All boards were made with 0.5% wax. Immediately after pressing, the boards were weighed and measured for thickness. They were then placed in a plywood box for thermal equalization. The panel size was 609.6 x 711.2 x 12.7-mm.

Specimen Preparation and Testing Procedure

Flake Alignment Distribution. - A strip of 50.8-mm was trimmed from the four sides of each panel to reduce the edge effects on test specimens. A clear plastic sheet, marked with a 50.8 x 50.8-mm dot grid was placed on the top surface of each board. One flake from each grid square was randomly selected and a line representing the flake was drawn on the plastic film parallel to the long dimension of the flake. The plastic film was then placed on a drafting table and a protractor was used to measure orientation of each line. Flake angles measured varied from -90° to 90° with 0° set along the major alignment direction. A total of 143 flakes were measured for each panel.

Density Gradient.- Three 50.8 x 50.8 x 12.7-mm specimens were cut from each panel, totaling 132 specimens for 44 panels. Density profile in the specimen thickness direction was determined on a Quintek Density Profile Model QDP-01X. This equipment is an x-ray based precision instrument for making density profile measurements in wood composites. The profiler uses an x-ray tube operating in a range of 40 kV to produce a photon beam for density determination.

Linear Expansion. -Two samples, 25.4 x 304.8 x 12.7-mm, were cut along each of the two principal directions from each board, totaling 88 samples for each direction. This gave four replications for each combination of density, flake alignment level and resin content (RC). They were numbered according to board type, material direction (parallel or perpendicular) and replication number. Two holes (1.1-mm in diameter) 254-mm apart were drilled along the long dimension of each specimen and a small rivet (1.0-mm in diameter), dipped in epoxy glue, was plugged into each of the two holes. After the glue set, one reference cross was carefully cut on the tip of each rivet using a sharp razor blade. The cross facilitated LE measurements with an optical comparator.

All specimens were initially dried in a convection oven at 60°C to reach a constant weight. Measurements including specimen weight, length, width, thickness and reference dimension between the two rivets of each specimen were made at the dry state. The specimens were conditioned to reach equilibrium at each of the five RH levels: 35%, 55%, 75%, 85% and 95%. They were then subjected to a 48-hour water soak (WS) treatment. Finally, all specimens were oven-dried for 24 hours at 105 °C.

The measurements were repeated at each specified RH level, WS and oven-dry (OD) condition.

Bending test. - Static bending specimens, 76.2 x 355.6 x 12.7-mm, were cut along two principal directions of each panel according to ASTM D1037-96. One parallel and one perpendicular specimen from each panel were prepared, totaling 44 specimens for each direction. This gave two replications for each combination of density, alignment level and RC. The specimens were conditioned to reach equilibrium at 45% RH and 25°C. Their weight and size (i.e. length, width and thickness) were measured before testing. Bending tests were made on a Model 4260 INSTRON machine with a computer controlled data acquisition system. After breaking, a 50.8 x 76.2-mm section was cut from each end of each sample for further testing. The rest of the specimen was weighed and oven-dried to determine its MC on the OD basis.

Data Analysis

Flake Alignment Distribution. - The underlying flake orientation distribution for the test panels is assumed to be the von Mises probability distribution [1]. To obtain the concentration parameter, alignment percent defined by Geimer [2] and mean flake angle among the number of flakes measured were calculated for each panel. The look-up table published by Shaler [7] with the alignment percent and mean angle as input was used to obtain the concentration parameter.

Linear Expansion and MOE/MOR. - Linear expansion was calculated as

$$LE = \left[\frac{L_l - L_O}{L_O}\right] x\ 100\% \qquad [1]$$

where, LE is expressed in % (mm/mm), L_l is the reference dimension at a given RH level (mm) and L_O is the reference dimension at the reference RH level (mm). LE data were presented in two formats: LE as a function of MC from dry to equilibrium condition at 95% RH; and total LE value from OD to WS condition. Bending MOE and MOR were calculated by the testing program after each test.

LE as a function of MC, total LE from OD to WS condition and MOE/MOR were expressed as a function of processing variables using SAS [6] as:

$$P = a\ RC^b\ \kappa^c\ SG^d\ MC^e \qquad [2]$$

where

- P = property: LE (%) or MOE (GPa) or MOR (MPa);
- RC = resin content (%);
- κ = concentration parameter for the von Mises distribution;
- MC = moisture content (%);
- a, b, c, d, and e = regression constants.

In fitting Equation 2, natural logarithm transformation of both dependent variables (LE, MOE or MOR) and independent variables (RC, κ, SG and MC) was first performed. A linear regression analysis was then made.

RESULTS AND DISCUSSION

Flake Alignment Distribution

Figure 1 shows measured flake orientation distributions for boards at the three alignment levels. The mean angle for all panels was within ±5°. An assumption of a 0° mean angle was thus made to look up the concentration parameter [7].

The concentration parameter, κ, averaged at 9.23, 2.34 and 0.13 for the boards with high, low and random alignment levels respectively (Table 2). The corresponding alignment percent was 82.3%, 61.3% and 5.2%. There was a large drop in κ value between 82.3% and 61.3% alignment levels. This was due to the nature of the von Mises distribution itself [1]. As the alignment level further increases, κ increases sharply and becomes infinite at the 100% alignment level. Also shown, random boards were not completely random (i.e. κ was not equal to zero) according to the measured flake orientation distribution.

As the value of κ decreased, a greater percentage of flakes became randomly distributed. This quantity can thus be used to correlate both physical and mechanical properties of the panel with flake orientation distribution. The experimental fact that the accumulative distribution curves for OSB follow a common mathematical rule is of special significance as analytical expressions for physical and mechanical properties may be calculated and compared with experimental results.

Density Gradient

Figure 2 shows measured density distribution across board thickness for boards at various density levels. As shown, vertical density gradient was effectively eliminated by using a cold press at closing. Subsequent heating after press closure did not cause a significant density gradient inside the panel. Absence of density variation across board thickness allows the study of effects of board density alone on both physical and mechanical properties. From this, layer properties as a function of density can be established to simulate individual layers in three-layer boards with vertical density gradient.

Relationship Between LE and MC Change

The shape of LE-MC change curve depends on alignment level and material direction (Fig. 3). For the high alignment boards shown (κ=11.5, Fig. 3a), LE in the perpendicular direction followed a nearly linear relationship with MC change. This relationship agrees with well-established linear MC-shrinkage/swelling relationships in the transverse directions for solid wood [9]. LE in the parallel direction followed a curve-linear relationship with MC change (Fig. 3a). The swelling rate was larger at lower MC levels and decreased as MC levels increased. This can be seen as the LE-MC curve leveled off toward the MC change axis at higher MC levels. The small magnitude of LE in the parallel direction and its curve-linear relation with MC change reflected the true longitudinal wood swelling [5]. Therefore, high alignment boards swelled in the plane of the panel much like solid wood.

As the flake alignment level decreased, LE decreased in the perpendicular direction and increased in the parallel direction (Fig 3b for $\kappa = 2.35$). This was due to an increased percentage of flakes turning away from the major alignment direction. In the perpendicular direction, the LE-MC change relationship became curve-linear. This change in the shape of the curve clearly demonstrated the dominant effect from the longitudinal direction. It not only changed the magnitude of swelling, but also changed the shape of the curve. This provides further evidence that longitudinal swelling controls the in-plane movement in wood composite panels.

For the random boards (Fig 3c for $\kappa = 0.145$), LE curves from both directions overlapped indicating more uniform in-plane swelling properties. Again, a curve-linear relation was observed. Board density and resin content had little effect on the shape of the curve.

Most OSB products have a flake alignment level falling between high and random alignment boards shown above. They all process a similar curve-linear LE-MC change relationship, provided that they are properly made [10]. As a result, departure in the shape of the curve from the one with a falling rate would reflect some internal structural changes due to moisture-related swelling. For example, if a panel has an LE-MC curve with a swelling rate increasing with MC (i.e. the curve convex toward the MC change axis), excess structural damage must have occurred inside the panel. Therefore, the shape of LE-MC change curves provides a way to check the integrity of the panel under swelling conditions.

Effect of Flake Alignment Level on LE and MOE/MOR

The dependence of LE from OD to WS condition, MOE and MOR on flake orientation distribution is summarized in Table 2 and Table 3. Figures 4a, 4b and 4c show, respectively, plots of LE, MOE and MOR as functions of κ for the panels at 4% resin content level. The magnitudes of the LE and MOE/MOR were strongly influenced by flake orientation distribution.

With decreases in κ, indicating that more flakes were aligned toward the direction perpendicular to the major alignment direction, LE decreased in the perpendicular direction and increased in the parallel direction (Fig 4a). Opposite to LE, MOE and MOR increased in the perpendicular direction and decreased in the parallel direction (Fig 4b and 4c). Both LE and MOE/MOR in the two principal directions reached a similar value for random boards.

The rate of change in LE, MOE and MOR in relation to the change in flake orientation distribution or alignment level varied with material direction and degree of alignment. In the parallel direction, the average rate of change for each property (LE, MOE or MOR) was much similar for the two given alignment ranges at each RC level (Table 4). In the perpendicular direction, however, the rate at the higher alignment level (alignment percent > ~60% or κ > ~2.3) was more than two to three higher than that at the lower alignment level (alignment percent < 60% or κ < ~2.3). This suggested that in the parallel direction property change occurred more uniformly over the entire alignment range. In the perpendicular direction, however, there was more dramatic change in all three properties at the higher alignment level. The rate of change slowed down considerably once the alignment level decreased at about 60% alignment level.

The large rate increase of LE value in the perpendicular direction for the panels at higher alignment levels may not cause significant problems in three-layer boards. This is because their strength properties decreased at the same time. Under cross-lamination, their large swelling potential will be restricted by the flake layers running perpendicular to them.

Effect of Board Density on LE and MOE/MOR

The dependence of the LE, MOE and MOR on panel density is summarized in Table 2 and Table 3. Data of LE, MOE and MOR as a function of density were plotted in Figures 5a, 5b and 5c, respectively.

For the aligned boards, there was an increase in LE along the perpendicular direction and a decrease in LE along the parallel direction with increases in panel density (Table 2 and Figure 5a). For the random boards, the trend was less obvious. Thus, with single-layer OSBs of uniform density, panel density not only influenced LE value, its effect also varied with material directions.

Earlier works quoted by Kelly [3] did not show a consistent relationship between LE and density. This may be due to the presence of density gradient and cross-lamination in the study panels manufactured under hot pressing. As shown earlier, density effect on LE varied with material directions. Under cross-lamination, the effects from the two directions cancel each other. Depending on the material direction actually measured and density difference in the face and core layers, LE of the panel may increase or decrease with increased panel density.

The peculiar behavior of LE in relation to panel density for the test panels may be explained at the cellular level. Under pressure and heat as used in hot pressing, cell lumina and/or vessels in hardwoods would collapse and fractures in cell walls would develop. As a result, the amount of wood material and wood-to-wood contact in the plane of a panel would increase. This process is likely to occur at an increased intensity with increased panel density. Under the swelling condition, the increased amount of wood material in the plane of the panel would lead to a larger swelling in the perpendicular direction, which explains why the perpendicular LE increased with panel density. In the parallel direction, however, wood is much stronger and swells much less. The effect of increased wood-to-wood contact (leading to better bonding and less movement) outweighed the effect of increased wood material in the plane. As a result, LE decreased with panel density in the parallel direction. It should be pointed out that for a three-layer panel, effect of cross lamination plays a significant role in controlling the LE.

As expected, MOE/MOR in both parallel and perpendicular directions increased linearly with specific gravity. The result agrees with earlier research results in the field [2,3]. This is commonly attributed to the increase of wood material for a given board volume at higher density levels.

Effect of Resin Content on LE and MOE/MOR

Resin content is often believed to play a key role in helping stabilize the panel under the swelling condition. However, for the two resin content levels used in the study, there appeared to be no significant effect in LE values along both material directions (Figures 6a and 6d). This seems to agree with the earlier finding [3] that except at extremely low resin contents where LE is substantially increased, above a resin content high enough to adequately bond the particles, further resin addition is of little benefit to this property.

The effects of resin content on MOE/MOR also appeared to be insignificant at the given resin content levels (Table 3 and Figures 6b, 6c, 6e, and 6f). Further experiments are underway to examine effects of resin content on the long term swelling and strength retention behaviors of these products.

Fitting the Data

Table 5 summarizes the regression results among LE, MOE, MOR and various processing variables. Typical plots of fitted lines are shown in Figures 4 and 5. In general, the power form relationship fitted MOE and MOR data better compared with the LE data. This was due to larger variability in the LE data. The analytical functions established provide a means to relate various properties to processing variables for modeling three-layer panels.

SUMMARY AND CONCLUSIONS

Linear expansion in OSB occurred as a result of complex interactions between various processing variables and MC increases. Excess movement in the plane of a panel can cause high internal stresses when it is totally or partially restrained. The study described here investigates effects of flake orientation distribution, density, resin content and MC levels on LE, MOE and MOR of single layer OSBs.

It was found that the shape of the LE-MC change curve varied with alignment level and material directions. The variation was attributed to the difference in the controlling mechanism for LE in various panels. LE from OD to WS condition, MOE and MOR were found to vary significantly with flake orientation distribution and density, but not resin content. LE, MOE and MOR were correlated with flake orientation distribution, density, resin content and moisture content through a power form equation. Future publications will discuss in-plane stability of three-layer, cross-laminated OSBs with vertical density gradient.

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Table 1. Board Fabrication - Single Layer Uniform Density Boards.

Board Type [a]	Target board density (g/cm^3)	Resin content [b] (%)	Number of replication	Number of boards made
HAL	0.55, 0.75, 0.95, 1.15	4, 6	2	16
LAL	0.55, 0.75, 0.95, 1.15	4, 6	2	16
RAL	0.55, 0.75, 0.95	4, 6	2	12

[a] HAL - High alignment level; LAL - Low alignment level; RAL - Random alignment level.
[b] Based on oven-dry flake weight.

Table 2. Summary of LE data from oven-dry to soaked condition.

Board Type [a]	Alignment level: Percent [b]	Alignment level: κ [c]	Parallel: Density [d] (g/cm³)	Parallel: LE (%)	Perpendicular: Density (g/cm³)	Perpendicular: LE (%)	LE Ratio [e]
			4% Resin Content				
HAL	84.6	11.52	0.51 (0.02)	0.20 (0.04)	0.58 (0.03)	2.12 (1.05)	10.60
	82.5	9.69	0.76 (0.02)	0.13 (0.05)	0.75 (0.02)	3.30 (0.40)	25.38
	82.1	9.04	0.96 (0.02)	0.15 (0.04)	0.98 (0.03)	3.17 (0.74)	21.13
	81.8	8.66	1.18 (0.03)	0.12 (0.08)	1.21 (0.04)	3.23 (1.23)	26.92
LAL	61.2	2.33	0.59 (0.02)	0.22 (0.08)	0.61 (0.01)	0.83 (0.10)	3.77
	63.1	2.49	0.75 (0.04)	0.22 (0.04)	0.79 (0.02)	0.87 (0.11)	3.95
	60.8	2.29	0.97 (0.02)	0.20 (0.06)	0.89 (0.04)	0.98 (0.18)	4.90
	62.3	2.42	1.13 (0.02)	0.16 (0.02)	1.18 (0.02)	1.28 (0.48)	8.00
RAL	5.86	0.15	0.52 (0.03)	0.39 (0.03)	0.59 (0.03)	0.30 (0.13)	0.77
	8.35	0.21	0.71 (0.01)	0.31 (0.11)	0.79 (0.02)	0.28 (0.07)	0.90
	6.21	0.15	0.90 (0.01)	0.35 (0.09)	0.93 (0.03)	0.41 (0.07)	1.17
			6% Resin Content				
HAL	82.8	9.69	0.54 (0.02)	0.21 (0.04)	0.54 (0.01)	2.88 (0.74)	13.72
	82.6	9.73	0.76 (0.04)	0.16 (0.05)	0.84 (0.01)	3.07 (0.56)	19.19
	81.6	8.49	0.97 (0.06)	0.12 (0.06)	0.99 (0.02)	2.96 (0.55)	24.67
	80.2	7.05	1.19 (0.04)	0.11 (0.12)	1.16 (0.02)	3.33 (0.93)	30.27
LAL	59.5	2.18	0.61 (0.02)	0.21 (0.07)	0.60 (0.02)	0.87 (0.19)	4.14
	61.7	2.36	0.78 (0.01)	0.23 (0.04)	0.76 (0.03)	0.89 (0.08)	3.87
	60.9	2.29	0.96 (0.02)	0.20 (0.05)	1.00 (0.03)	1.13 (0.41)	5.65
	60.8	2.33	1.11 (0.08)	0.17 (0.08)	1.09 (0.06)	1.15 (0.36)	6.76
RAL	3.97	0.10	0.53 (0.02)	0.42 (0.03)	0.56 (0.01)	0.44 (0.14)	1.05
	5.25	0.13	0.70 (0.03)	0.37 (0.06)	0.73 (0.02)	0.32 (0.11)	0.86
	1.49	0.04	0.95 (0.05)	0.36 (0.05)	0.91 (0.03)	0.35 (0.13)	0.97

[a] HAL - High alignment level; LAL - Low alignment level; RAL - Random alignment level.
[b] Alignment percent follows the definition by Geimer [2].
[c] κ - Concentration parameter of the flake orientation distribution.
[d] Density - based on the oven-dry weight and volume at about 2% MC.
[e] LE ratio - LE in the perpendicular direction divided by LE in the parallel direction.

Table 3. Summary of test results on bending MOE and MOR.

Board Type [a]	κ	Parallel				Perpendicular				MOE Ratio [b]
		MC (%)	SG	MOE (MPa)	MOR (MPa)	MC (%)	SG	MOE (MPa)	MOR (MPa)	
4% Resin Content										
HAL	11.52	5.5	0.50	8305.5	51.96	5.5	0.60	608.5	5.83	13.65
	9.69	5.7	0.75	13317.5	82.67	5.6	0.75	1059.1	8.28	12.57
	9.04	5.7	0.92	15358.2	114.76	5.9	0.88	1392.4	12.89	11.03
	8.66	4.6	1.17	19133.1	141.62	6.1	1.08	2316.3	19.64	8.26
LAL	2.33	5.2	0.54	7270.6	45.91	5.2	0.53	1603.1	13.89	4.54
	2.49	5.1	0.73	9349.4	61.43	5.1	0.72	2580.7	26.08	3.63
	2.29	5.6	1.03	13579.3	102.73	5.8	0.90	3064.7	31.08	4.43
	2.42	5.2	1.11	14472.2	106.94	5.8	1.07	3283.9	36.82	4.41
RAL	0.15	4.7	0.50	3703.2	23.83	5.0	0.56	4306.8	31.07	0.86
	0.21	4.8	0.73	5909.9	42.14	4.7	0.80	6396.9	45.35	0.92
	0.15	5.1	0.86	6874.8	49.54	5.8	0.90	6347.0	51.34	1.08
6% Resin Content										
HAL	9.69	5.3	0.52	8484.1	48.45	5.4	0.52	722.9	6.88	11.74
	9.73	5.6	0.73	12141.7	81.64	5.6	0.73	1256.9	12.22	9.66
	8.49	5.7	0.92	15134.1	120.18	5.9	0.92	1662.7	13.23	9.10
	7.05	4.4	1.14	20032.9	151.55	5.9	1.17	2454.2	24.24	8.16
LAL	2.18	5.1	0.53	7327.5	47.89	5.6	0.53	1821.3	18.29	4.02
	2.36	5.3	0.72	9607.9	65.54	5.3	0.75	2072.9	25.49	4.64
	2.29	6.1	0.99	12000.4	95.84	6.1	0.93	3070.9	33.82	3.91
	2.33	5.9	1.06	15764.9	120.35	6.3	1.05	3673.2	36.27	4.29
RAL	0.10	5.8	0.54	3744.6	27.54	5.0	0.59	5043.2	38.48	0.74
	0.13	4.5	0.65	5448.6	45.38	4.8	0.70	5975.7	49.09	0.91
	0.04	4.5	0.95	6874.8	49.54	5.8	0.99	7270.9	68.19	0.95

[a] HAL - High alignment level; LAL - Low alignment level; RAL - Random alignment level.
[b] MOE ratio - MOE in the parallel direction divided by MOE in the perpendicular direction.

Table 4. Rate of property change over the two alignment ranges. Data shown is in percent change from the value at the beginning alignment level in a given range over percent change in the alignment level.

Alignment Level		LE [a]		MOE		MOR		RC
Percent	κ	//	⊥	//	⊥	//	⊥	
83%-62%	9.73 - 2.38	1.77	- 3.19	- 0.85	6.01	- 0.76	7.85	4%
62%-7%	2.38 - 0.17	1.16	- 1.15	- 0.82	2.59	- 0.79	1.59	
82%-61%	8.74 - 2.29	1.75	- 3.22	- 0.88	4.79	- 0.66	6.81	6%
61%-4%	2.29 - 0.09	1.40	- 1.07	- 0.88	2.94	- 0.87	1.78	

[a]. Negative numbers mean a decrease in the property and positive numbers mean an increase in the property.

Table 4. Regression Results - LE, MOE or MOR = a RC^b SG^c κ^d MC^e

Material Direction	Properties	Regression Constants					r^2
		a	b	c	d	e	
Parallel	LE (%)	0.02837	-0.1877	-0.7706	-0.1616	0.5890	0.80
	LE (OD-WS, %)	0.1519	0.8200	-0.8075	-0.1665	—	0.54
	MOE (GPa)	10.9480	0.0635	1.1547	0.1419	—	0.96
	MOR (MPa)	57.3969	0.2827	1.2675	0.1358	—	0.95
Perpendicular	LE (%)	0.0500	0.4839	0.62855	0.3281	0.7215	0.80
	LE (OD-WS, %)	0.4286	0.5227	0.4764	0.3986	—	0.74
	MOE (GPa)	4.2638	-0.1003	1.1543	-0.2852	—	0.85
	MOR (MPa)	25.8525	0.1616	1.2479	-0.2567	—	0.80

FIGURE CAPTION:

Figure 1. Measured flake orientation distributions for the test panels at high, low and random alignment levels.

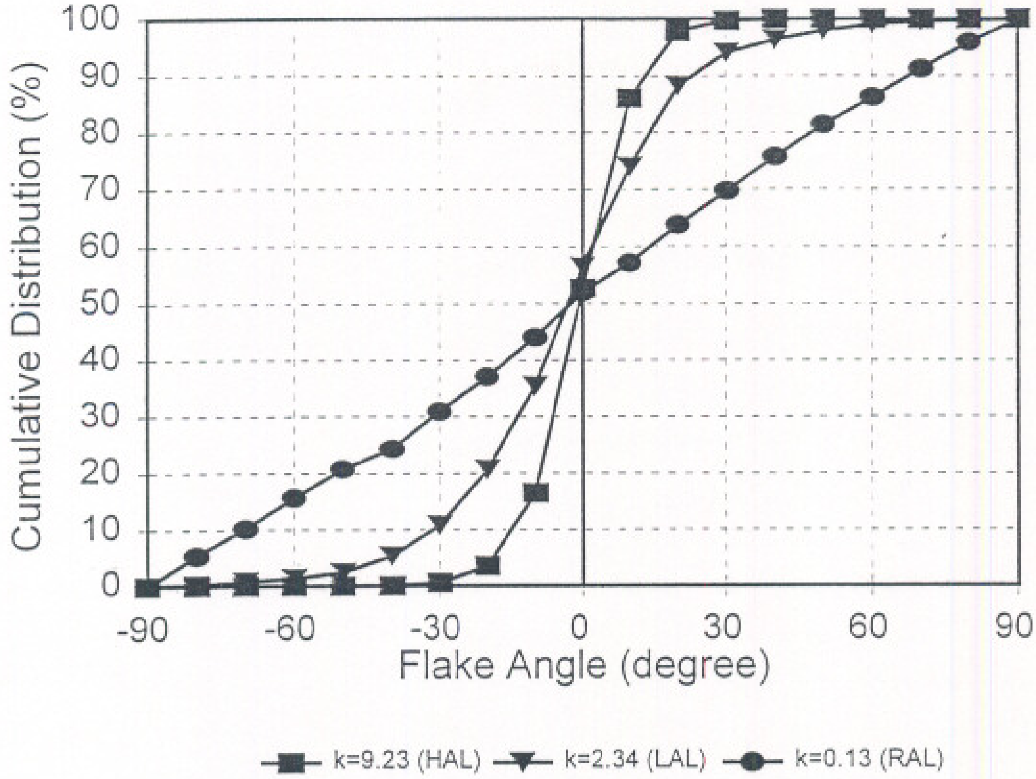
Figure 2. Measured density profiles across board thickness for the test panels at various density levels.

Figure 3. Typical LE-MC change relationships for the test panels at high (a), low (b) and random (c) alignment levels.

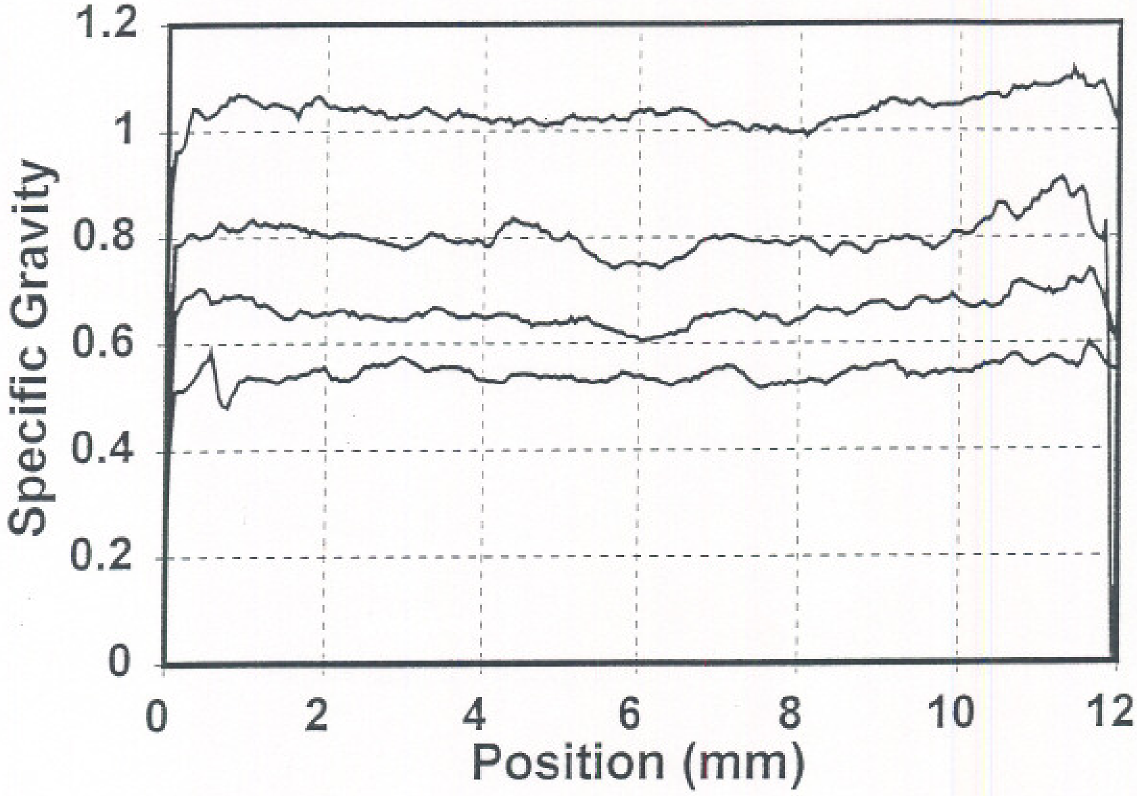
Figure 4. Dependence of LE from OD to water-soak condition (a), MOR (b) and MOE (c) on the concentration parameter. Lines show fitted values.

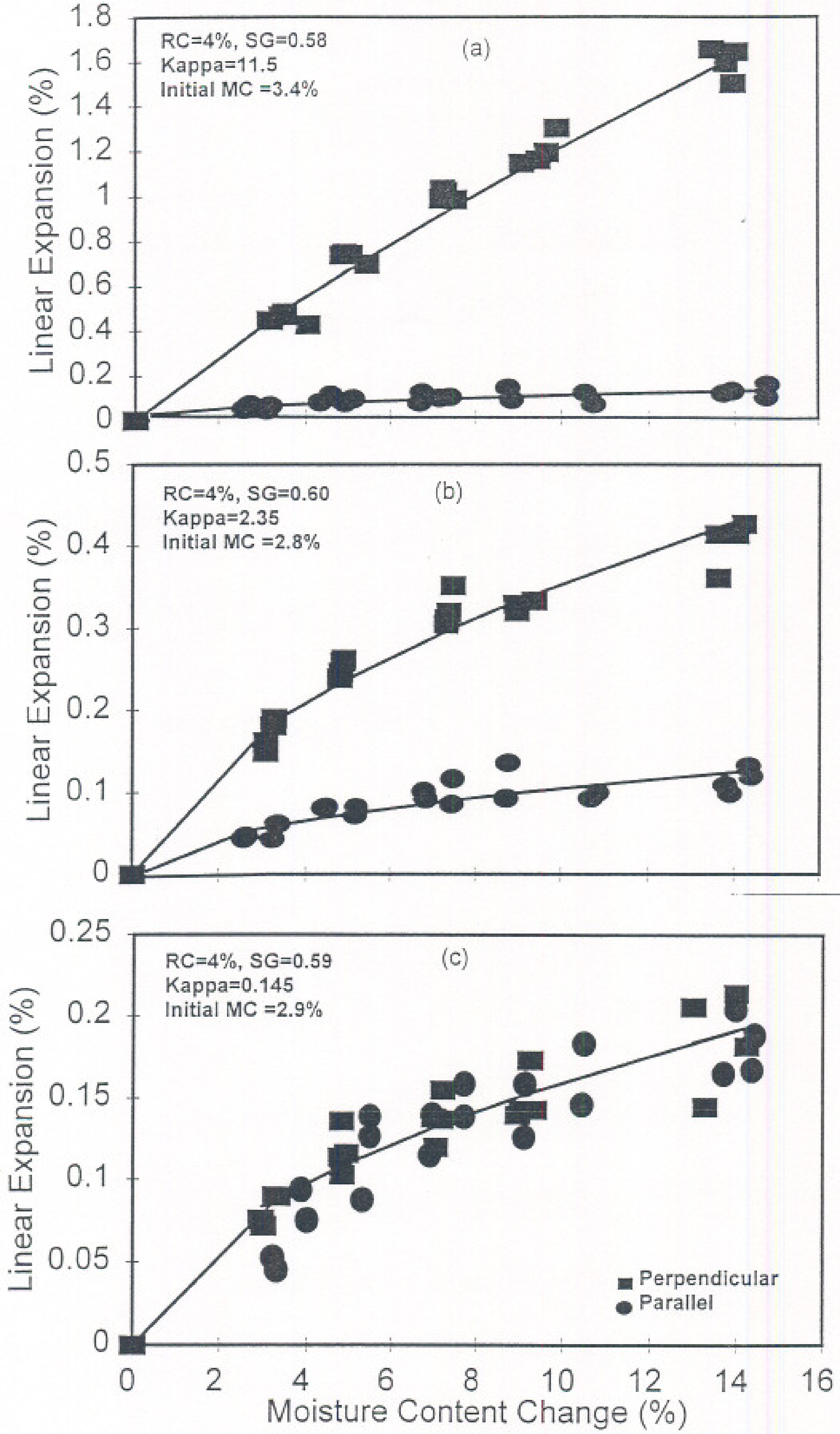
Figure 5. Dependence of LE from OD to water-soak condition(a), MOR (b) and MOE (c) on panel density. Lines show fitted values.

Figure 6. Dependence of LE from OD to water-soak condition(a), MOR (b) and MOE (c) on resin content.

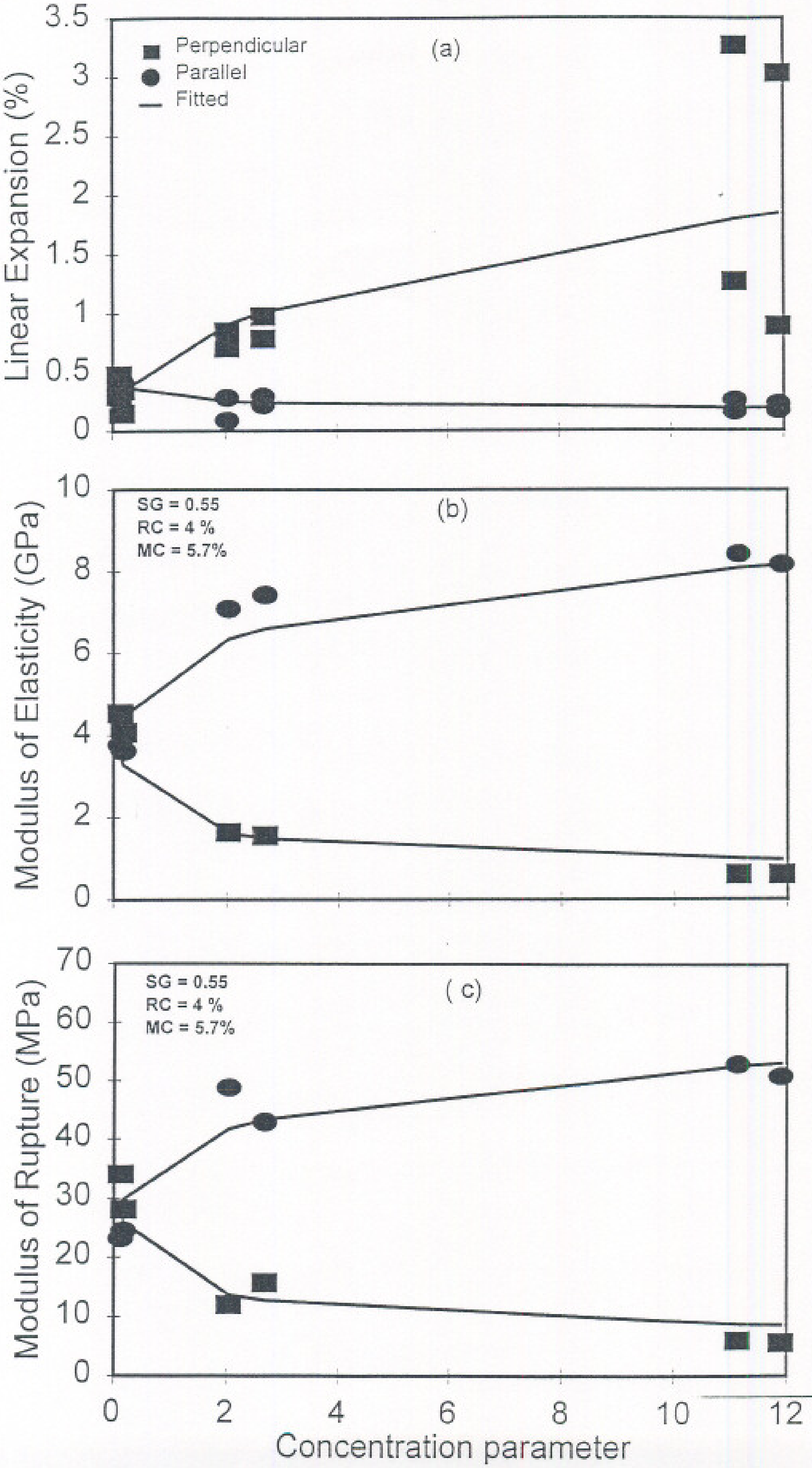


Cumulative Distribution (%)
100
90
80
70
60
50
40
30
20
10
0
-90
-60
-30
0
30
60
90
Flake Angle (degree)
k=9.23 (HAL)
k=2.34 (LAL)
k=0.13 (RAL)

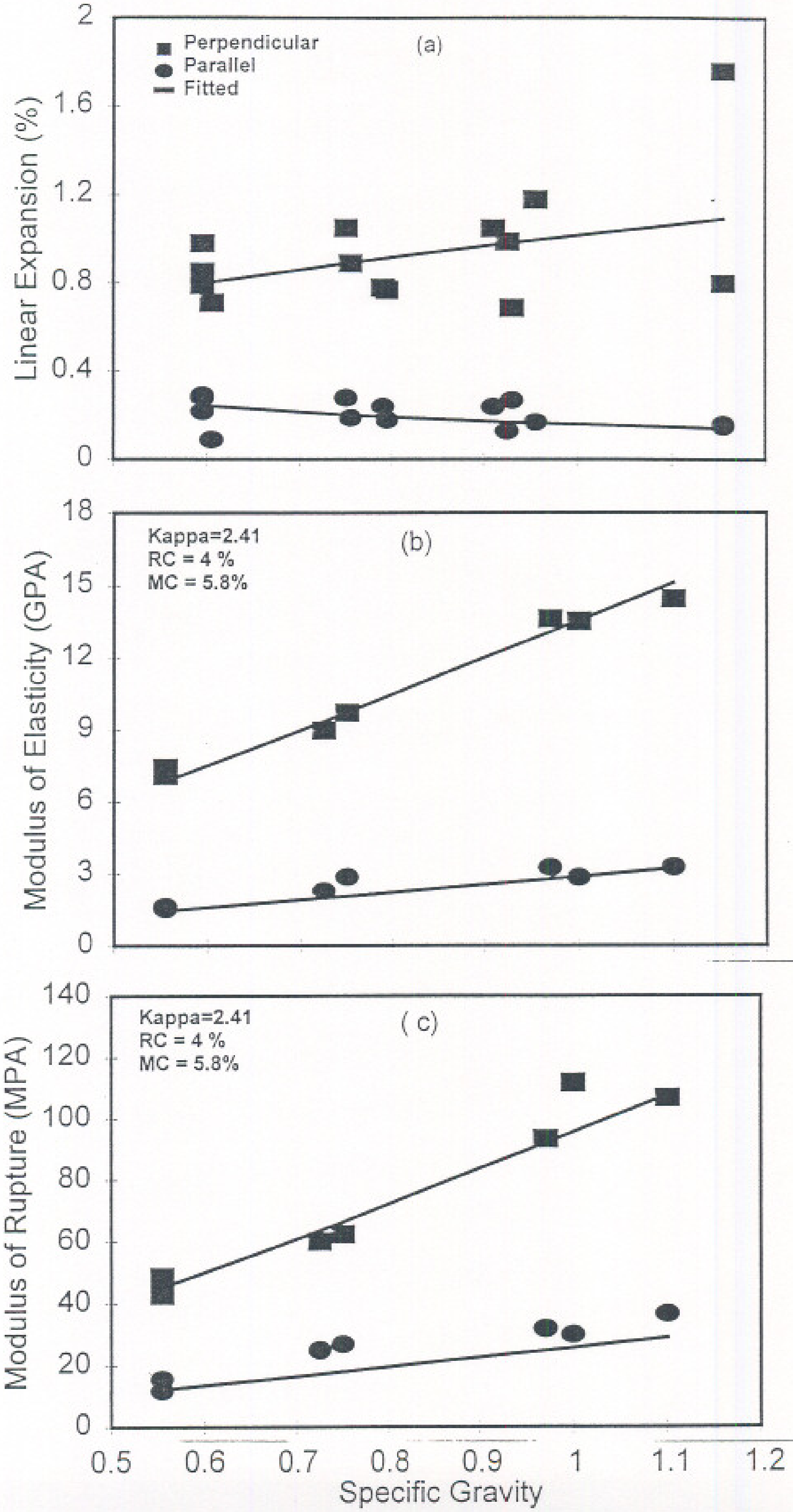

1.2
1
0.8
0.6
0.4
0.2
0
Specific Gravity
0
2
4
6
8
10
12
Position (mm)



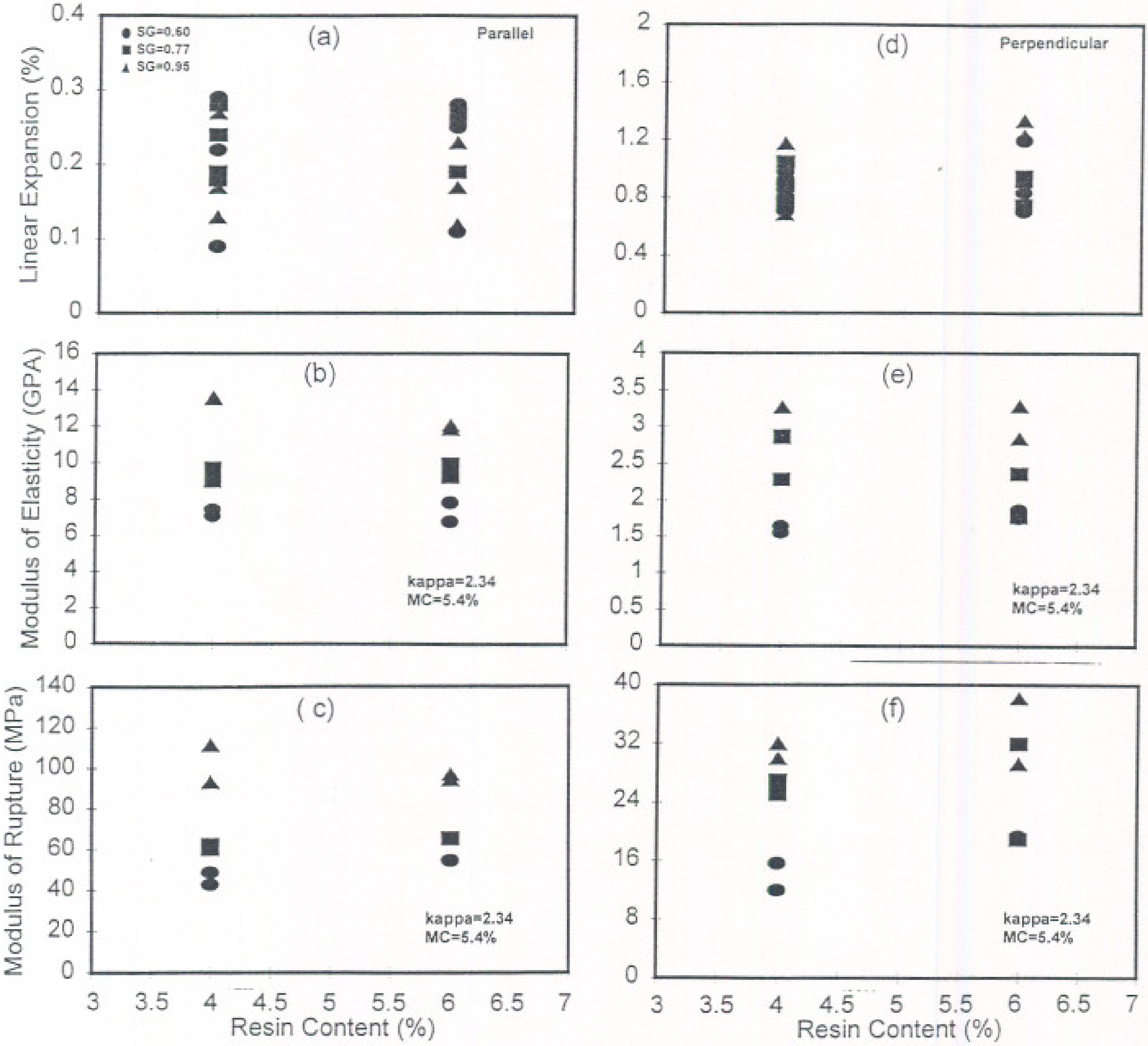
RC=4%, SG=0.58
Kappa=11.5
Initial MC =3.4%
(a)
RC=4%, SG=0.60
Kappa=2.35
Initial MC =2.8%
(b)
RC=4%, SG=0.59
Kappa=0.145
Initial MC =2.9%
(c)
Perpendicular
Parallel
Linear Expansion (%)
Moisture Content Change (%)



Perpendicular
Parallel
Fitted
(a)
Linear Expansion (%)
SG = 0.55
RC = 4 %
MC = 5.7%
(b)
Modulus of Elasticity (GPa)
SG = 0.55
RC = 4 %
MC = 5.7%
(c)
Modulus of Rupture (MPa)
Concentration parameter



Perpendicular
Parallel
Fitted
(a)
Linear Expansion (%)
2
1.6
1.2
0.8
0.4
0
Kappa=2.41
RC = 4 %
MC = 5.8%
(b)
Modulus of Elasticity (GPA)
18
15
12
9
6
3
0
Kappa=2.41
RC = 4 %
MC = 5.8%
(c)
Modulus of Rupture (MPA)
140
120
100
80
60
40
20
0
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
Specific Gravity



SG=0.60
SG=0.77
SG=0.95
(a)
Parallel
Linear Expansion (%)
(d)
Perpendicular
(b)
Modulus of Elasticity (GPA)
kappa=2.34
MC=5.4%
(e)
kappa=2.34
MC=5.4%
(c)
Modulus of Rupture (MPa)
kappa=2.34
MC=5.4%
(f)
kappa=2.34
MC=5.4%
Resin Content (%)
Resin Content (%)