MODELING MOISTURE CONTENT-MECHANICAL PROPERTY RELATIONSHIPS FOR CLEAR SOUTHERN PINE

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ABSTRACT

The objective of this study was to determine the effect of moisture content on a wide range of clear wood properties. Specimens were cut from commercially dried 38- by 140-mm (nominal 2- by 6-in.), southern pine lumber and sorted, based on specific gravity, into five matched moisture groups of approximately 40 specimens each. Empirical models are presented for predicting the effect of moisture content on strength and stiffness for the various test properties. Results indicate that tensile stress parallel- and perpendicular-to-grain and both Mode I and Mode II stress intensity factors for fracture toughness increase with decreasing moisture content from green to a peak between 7% and 13% moisture content. Upon additional drying, these properties decrease. Maximum fiber stress in bending, compression parallel- and perpendicular-to-grain, shear parallel-to-grain, and all elastic modulii increase with decreasing moisture content from green to 4% moisture content. For some of these properties, the increase is not linear at lower moisture content levels. Because specific gravity is known to affect clear wood properties, models were also developed to account for using moisture content and specific gravity. Theoretical approaches to moisture absorption that may explain experimental results are discussed.

Keywords: Moisture content, specific gravity, clear wood, tension, bending, compression, shear, stress intensity factor, Poisson's ratio, southern pine, empirical models, dimension lumber, drying.

INTRODUCTION

In the United States, lumber equilibrates to a wide range of moisture content (MC) levels in use. For example, lumber installed green in timber bridges may remain at or near the fiber saturation point for several years after bridge installation. In contrast, lumber used in attics in the dry southwestern parts of the country or over heat sources in commercial buildings may be reduced to moisture levels as low as 2% to 4% the year after installation. This study is part of a program to gain a fundamental understanding of the effect of MC on the mechanical properties of wood. The program was initiated because: (1) previous research indicates that lumber strength, especially ultimate tensile stress (UTS) parallel-to-the-grain, does

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not always increase with decreasing moisture content, and (2) limited, but persistent, failures have been reported in timber structures subjected to environmental conditions that lead to very low MC levels.

Each year, for the past 15 years, the Forest Products Laboratory has received one to three inquiries about failures in structural members that were subjected to ambient environmental conditions that resulted in member MC levels in the range of 2% and 4%. A significant number of these inquiries are from consulting engineers knowledgeable in the design of wood structures. Some telephone inquiries may be followed by written reports, including pictures, or receipt of samples of wood cut from failed members. Virtually all these inquiries involve commercial buildings. Some member failures have occurred at connections, but a surprising number have also exhibited failure in the middle of the member far removed from a joint. In some instances, there is evidence of thermal degradation, and in others, no evidence of thermal degradation. However, in each member failure, low MC was suspected as a contributing factor.

In the past few years, several studies have been conducted on the effect of MC on the bending, tensile, and compressive strength of nominal 38-mm- (2-in.-) thick commercial lumber (Green and Evans 1989; Barrett and Lau 1991). This work established that bending and tensile strength did not necessarily increase with decreasing MC. For example, UTS parallel-to-grain, at most percentile levels, first increases with decreasing MC below the fiber saturation point and then decreases as MC falls below about 10% to 15% (Green et al. 1990). However, the experimental design of this research was driven by the needs of the U.S. In-Grade Testing Program (Green 1983). Because only a small amount of structural lumber is intentionally dried to less than about 10% MC, this level was the lowest MC for which UTS data were obtained.

Persistent reports of structural failures at low MC levels, coupled with the experimental evidence of a decrease in lumber strength at lower MC levels, suggest the need for a better understanding of the effect of MC on properties, especially UTS at low MC levels. The objective of this study was to determine the effect of MC on a wide range of clear wood properties. Empirical models fit to these data will serve as input to an analytical model that predicts strength (Cramer and McDonald 1989) for comparison with lumber MC test results.

BACKGROUND

Experimental studies on the effect of low MC on the UTS of structural lumber are expensive and time-consuming. The need to obtain a more fundamental understanding of the effect of MC on properties was recognized by Dr. David W. Green in the mid- 1980s. However, other priorities and the lack of an adequate analytical model to predict the strength of lumber using fundamental mechanisms prevented such a study at that time.

Considerable literature exists on the effect of MC on the mechanical properties of clear, straight-grained wood. A detailed discussion of the literature is contained in Green and Kretschmann (1994). In general, in any one study, data are given for only a few properties, and only a limited number of specimens were tested for a given property-MC combination. The number of researchers who have data on properties of clear wood at less than 6% MC is much more limited than those with data greater than 6% MC. From the studies reported (Green and Kretschmann 1994), it appears that modulus of elasticity (MOE) in bending and compressive strength parallel- and perpendicular-to-grain increases linearly with drying below the fiber saturation point. Some data indicate that the MOE parallel- and perpendicular-to-grain MC curves flatten for levels less than about 6% MC. Tensile strength parallel- and perpendicular-to-grain, shear strength parallel-to-grain, and Mode I and II fracture toughness also increase with decreasing MC from green to about 12% to 15%. Several studies have indicated that a significant decrease in these clear wood property values may occur with additional drying (Green and Kretsch-

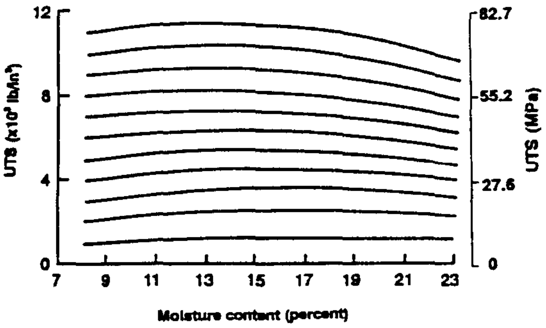

FIG. 1. Moisture effects on ultimate tensile strength (UTS) of dimension lumber (Green et al. 1990).

mann 1994). These property-value decreases could explain the loss in the UTS of lumber at MC levels less than 12% (Fig. 1).

This paper presents empirical equations relating clear wood properties to MC and specific gravity using the clear wood property data developed in the first part of our research (Green and Kretschmann 1994).

EXPERIMENTAL METHODS

Traditionally, clear specimens for MC property studies have been cut from green logs and then slowly dried to various target MC levels. However, the intended use of these data is to model tensile strength-MC relationships for structural lumber. The majority of commercial lumber is dried in a dry kiln using commercial schedules. After drying, when the lumber is used in a structure, designers need to know the effect of MC on the mechanical properties. The degree to which kiln schedule, moisture hysteresis, and other practical considerations affect the tensile strength of structural lumber is not precisely known (Eskelson et al. 1993; Hui and Smith 1991; Wilson 1932). So that our models might incorporate these unknown effects, we cut clear samples from previously dried structural lumber. We chose southern pine because it is a locally available, commercially important species for which no data exist on the relationship between MC and tensile strength of stress-rated lumber at low MC levels. The lumber was grade-stamped at mills that used conventional (≤ 82°C), not high temperature (≥ 110°C), drying schedules. Specimen preparation, dimensions, and testing procedures are described in detail in Green and Kretschmann (1994).

Material selection

Material for this study was cut from one hundred fifty 3.66-m- (12-ft-) long southern pine (either *Pinus echinata* or *P. taeda)* standard 38- by 140-mm (nominal 2- by 6-in.) lumber (hereafter designated as 2 by 6) obtained from local truss suppliers in Madison, Wisconsin. Care was taken to obtain flat-sawn lumber without pith. Produced at three mills, as based on the grade stamps, the lumber was either KD-15 (kiln-dried 15% maximum MC) Dense Select Structural or No. 1 Dense visually graded lumber (SPIB 1977).

The one hundred fifty 2 by 6 boards were numbered sequentially and equilibrated in a 26°C and 65% relative humidity (RH) conditioning room. Specific gravity based on ovendry weight and volume at MC was then obtained for each board. The boards were ranked according to specific gravity. To assign lumber to a specific MC cell, five 2 by 6 boards with the highest specific gravity were randomly assigned to one of five MC levels: one MC level was to be saturated; the other four MC levels required conditioning. The next five boards were selected and assigned randomly to their respective groups. This procedure was followed until all specimens were assigned to each moisture level cell. At least one (and possibly two) 132-cm- (52-in.-) long sections with straight grain and free from noticeable defects was cut from each 2 by 6.

The conditioned sections were placed into chambers with the appropriate temperature and RH to bring the wood to equilibrium at target MC levels of 4% (32°C and 20% RH), 8% (27°C and 30% RH), 12% (26°C and 65% RH), and 18% (27°C and 90% RH). The saturated material was obtained by water-soaking under a vacuum. To prevent excessive stain and the possibility of decay, the saturated material was

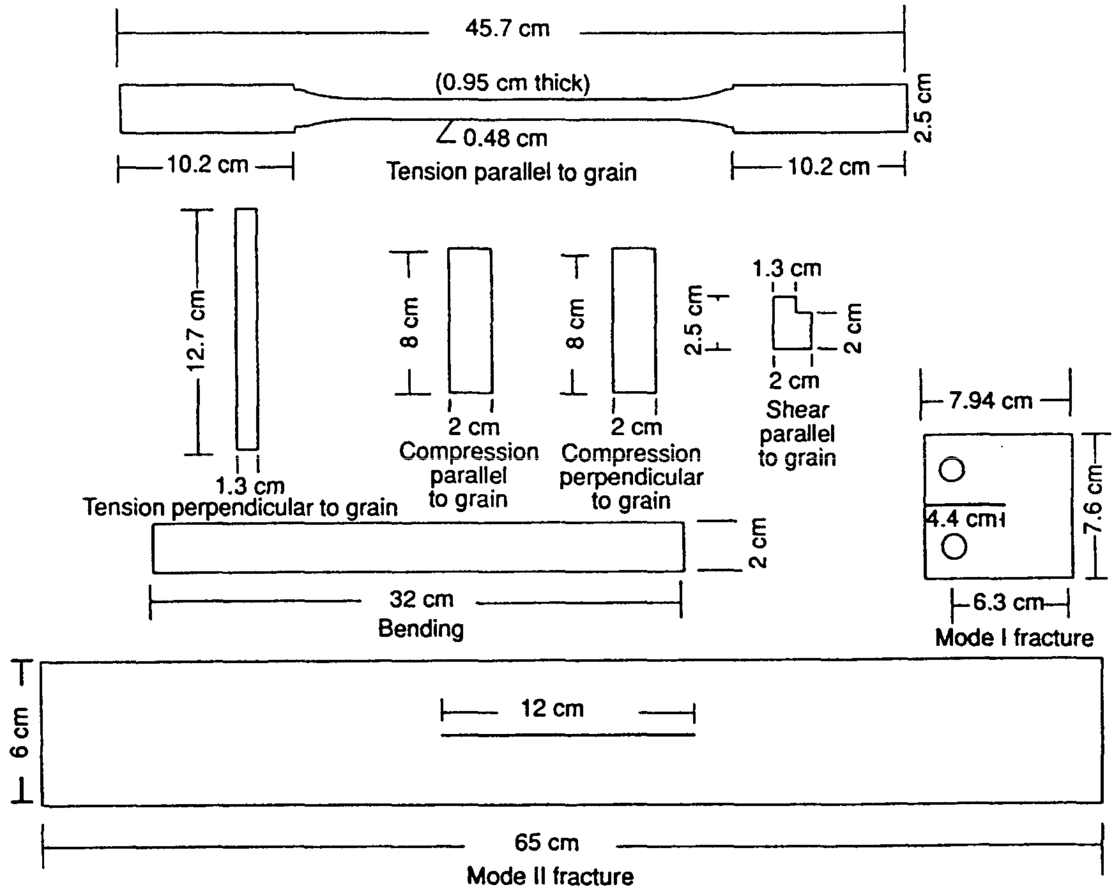

FIG. 2. Dimensions of test specimens.

stored in sealed bags in a cold room at 2°C and 82% RH prior to testing.

Specimen preparation

After equilibration, the 132-cm (52-in.) sections were planed to a thickness of 2.0 cm (0.787 in.). Nine specimen blanks were cut from the conditioned sections to be tested in tension parallel-to-the-grain, tension perpendicular-to-the-grain (two specimens, side by side), bending, compression parallel-to-the-grain, compression perpendicular-to-the-grain, Mode I fracture, Mode II fracture, and shear parallel-to-the-grain. The specimen cut-out pattern was arranged to keep the material with the straightest grain as close together as possible. For a detailed discussion of the specimen preparation, see Green and Kretschmann (1994).

Testing

Tension parallel-to-grain, center-point bending, compression, and shear tests were conducted on scaled specimens that conformed to the shapes specified in ASTM D 143 (ASTM 1993). Dimensions of the individual test specimens are given in Fig. 2. Poisson's ratio information was based on strain measurements of compression parallel specimens using analog extensometers. The tests were conducted on a universal test machine in a test chamber with a climate controlled by a portable AMINCO[2] conditioning unit. The unit maintained the temperature and MC levels at which the groups were conditioned. The saturated specimens were tested under controlled conditions of 26°C and 65% RH. For all tests, information was gathered to determine MC and specific gravity at the time of test (Green and Kretschmann 1994).

RESULTS

Results of the physical and mechanical property data are summarized in Tables 1–5.

Matching

The average density at 12% MC was 590 kg/m^3 (specific gravity at 12% = 0.53) for all MC levels (Table 1). This is slightly above the clear wood average of 570 kg/m^3 (specific gravity at 12% MC 0.51 (FPL 1987)) for loblolly or shortleaf pine. There was a good match among the specific gravity values in the different MC groups. All groups also had similar ranges for the specific gravity values.

Conditioning

A good separation between MC groups was obtained with little overlap in moisture levels (Table 2). The control capability of the various conditioning chambers governed the scatter present in MC results. The 4% and 8% levels had much tighter controls than did the 12% and 18% levels. The actual average MC levels for all groups (4.3%, 7.2%, 12.0%, and 18.1%) were close to the target MC levels (4%, 8%, 12%, and 18%). All saturated pieces were well above the fiber saturation point.

Curve fits

Test results are shown in Figs. 3 to 17. Average data points and boxplots are used to illustrate trends. Boxplots show the lowest datum point, the 25th percentile, the median, the 75th percentile, and the highest datum point. The boxplots were centered on the average MC for each moisture level. Individual data points within a moisture group were not adjusted to the average MC for the group before the percentiles were calculated. The average MC at which wood properties exhibit noticeable change rarely coincides with the wood fiber saturation point.

Determination of M_p. – The term M_p refers to an "effective" MC at which further drying has a significant effect on properties, but wetting has little or no noticeable effect. A procedure similar to the historic method (Wilson 1932) was used to establish the M_p values for our test material. For each property, strength data were plotted for the four dry MC levels. Visual inspection of the data suggested that a quadratic curve provided a good fit because of its nonlinear nature. An intercept between a horizontal line drawn through the average for the saturated data and the quadratic curve fit to the four dry MC data sets for each property was then calculated. A linear fit was used in M_p calculations for compression perpendicular-to-the-grain. From these results, we determined that 23% MC best represented an overall M_p value for this material (Green and Kretschmann 1994). The value of 23% compares favorably with the 21% M_p value that Wilson (1932) calculated. If Wilson had included his 4% data when determining M_p, his value for M_p would have been greater.

Moisture content-property relationships. – When the M_p value of 23% was determined, a quadratic curve was fit to all five MC groups having the following form:

$$\text{Property} = a(MC)^2 + b(MC) + c$$

where MC is to be entered as a percentage and a, b, and c are modeled coefficients.

Results of these curve fits are tabulated in Table 6. Extra digits are carried to avoid rounding errors in future computer simulations. The r^2 values ranged from 0.20 to 0.87.

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TABLE 1. *Mean, coefficient of variation (COV), minimum, and maximum data for density in kg/m^3 adjusted to 12% moisture content.*[a]

Moisture content level (%)	N	Density				Moisture content level (%)	N	Density				Moisture content level (%)	N	Density			
		kg/m^3 (mean)	COV	kg/m^3 (minimum)	kg/m^3 (maximum)			kg/m^3 (mean)	COV	kg/m^3 (minimum)	kg/m^3 (maximum)			kg/m^3 (mean)	COV	kg/m^3 (minimum)	kg/m^3 (maximum)
Tension parallel						Tension perpendicular						Modulus of rupture					
4	44	590 (0.52)	11.5	440 (0.39)	710 (0.63)	4		—	—	—	—	4	44	600 (0.53)	9.4	470 (0.42)	700 (0.63)
7	39	590 (0.53)	9.4	480 (0.43)	680 (0.61)	7		—	—	—	—	7	39	600 (0.54)	9.3	490 (0.44)	720 (0.64)
12	39	590 (0.53)	7.5	480 (0.43)	730 (0.65)	12		—	—	—	—	12	38	600 (0.54)	9.3	480 (0.43)	760 (0.68)
18	40	580 (0.52)	9.6	470 (0.42)	680 (0.61)	18		—	—	—	—	18	41	590 (0.52)	9.6	460 (0.41)	730 (0.65)
Saturated	43	590 (0.53)	7.5	480 (0.43)	660 (0.59)	Saturated		—	—	—	—	Saturated	43	620 (0.55)	9.1	460 (0.41)	730 (0.65)
Compression parallel						Compression perpendicular						Shear parallel					
4	41	590 (0.53)	9.4	490 (0.44)	720 (0.64)	4	44	590 (0.53)	11.3	470 (0.42)	690 (0.62)	4	41	590 (0.53)	11.3	480 (0.43)	710 (0.63)
7	39	600 (0.54)	9.3	480 (0.43)	700 (0.62)	7	40	600 (0.53)	11.3	470 (0.42)	700 (0.63)	7	39	600 (0.53)	11.3	470 (0.42)	720 (0.64)
12	38	600 (0.53)	7.5	520 (0.46)	750 (0.67)	12	39	600 (0.54)	9.3	480 (0.43)	750 (0.67)	12	39	600 (0.53)	7.5	490 (0.44)	760 (0.68)
18	38	570 (0.51)	9.8	450 (0.40)	690 (0.62)	18	42	580 (0.52)	9.6	470 (0.42)	710 (0.63)	18	42	570 (0.51)	9.8	450 (0.40)	690 (0.62
Saturated	40	610 (0.54)	9.3	480 (0.43)	710 (0.63)	Saturated	43	590 (0.53)	9.4	470 (0.42)	670 (0.60)	Saturated	41	590 (0.53)	9.4	470 (0.42)	690 (0.62)
K$_{Ic}$						K$_{IIc}$											
4	40	600 (0.53)	9.4	480 (0.43)	690 (0.62)	4	41	580 (0.52)	9.6	460 (0.41)	690 (0.62)						
7	38	600 (0.54)	9.3	470 (0.42)	690 (0.62)	7	40	600 (0.53)	11.3	460 (0.41)	720 (0.64)						
12	37	600 (0.53)	7.5	500 (0.45)	680 (0.61)	12	38	610 (0.54)	9.3	530 (0.47)	730 (0.65)						
18	40	580 (0.52)	9.6	470 (0.42)	690 (0.62)	18	40	580 (0.52)	11.5	460 (0.41)	710 (0.63)						
Saturated	42	610 (0.54)	9.3	460 (0.41)	690 (0.62)	Saturated	40	600 (0.53)	9.4	470 (0.42)	690 (0.62)						

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[a] — indicates no data; ( ) indicates specific gravity based on oven-dry weight and volume at 12% MC.

TABLE 2. *Mean, coefficient of variation (COV), minimum, and maximum data for moisture content.*

Moisture content level (%)	N	Moisture content				Moisture content level (%)	N	Moisture content				Moisture content level (%)	N	Moisture content			
		Mean	COV	Minimum	Maximum			Mean	COV	Minimum	Maximum			Mean	COV	Minimum	Maximum
Tension parallel						Tension perpendicular						Modulus of rupture					
4	44	4.4	4.5	4.1	4.9	4	30	4.2	2.3	3.9	4.4	4	44	4.5	4.4	4.0	4.9
7	39	7.6	2.6	6.8	7.9	7	35	6.7	3.0	6.0	7.1	7	39	7.7	3.9	7.1	8.6
12	39	12.0	11.6	9.6	15.9	12	35	11.9	8.4	9.9	13.3	12	38	11.9	9.2	9.8	13.4
18	40	18.3	7.1	15.9	20.4	18	34	18.7	5.3	16.7	20.9	18	41	17.7	9.6	10.7	20.6
Saturated	43	106.9	23.9	43.6	147.1	Saturated	40	104.9	20.6	62.7	149.9	Saturated	43	115.9	24.4	50.3	189.3
Compression parallel						Compression perpendicular						Shear parallel					
4	41	4.4	2.3	4.0	4.1	4	44	4.1	7.3	3.4	4.9	4	41	4.0	10.0	3.1	4.9
7	39	7.1	4.2	6.4	6.9	7	40	6.9	8.7	6.0	9.9	7	39	6.5	6.1	5.7	7.3
12	38	12.3	9.8	9.1	11.9	12	39	11.9	10.9	8.7	13.5	12	39	12.2	10.6	9.3	13.7
18	38	18.4	6.5	16.8	18.2	18	42	18.2	6.0	16.6	20.8	18	42	18.6	5.9	16.0	20.8
Saturated	40	108.2	28.1	46.0	111.5	Saturated	43	111.5	23.4	56.5	150.3	Saturated	41	106.8	24.8	52.0	149.2
K_{Ic}						K_{IIc}											
4	40	4.4	4.5	3.8	4.6	4	41	4.4	2.3	4.1	4.6						
7	38	7.4	2.7	6.6	7.7	7	40	7.4	2.7	6.7	7.9						
12	37	12.1	10.7	9.7	13.6	12	38	12.0	10.0	9.7	13.3						
18	40	17.5	7.4	15.7	19.8	18	40	17.5	7.4	15.2	20.4						
Saturated	42	109.9	23.0	51.5	147.1	Saturated	40	107.7	27.3	43.3	150.9						

TABLE 3. *Average data for strength.*[a]

Moisture content level (%)	Tension parallel MPa (lb/in^2)	Tension perpendicular MPa (lb/in^2)	Modulus of rupture MPa (lb/in^2)	Compression parallel MPa (lb/in^2)	Compression perpendicular MPa (lb/in^2)	Shear MPa (lb/in^2)	K_{Ic} KN·m$^{-3/2}$ (lb·in$^{-3/2}$)	K_{IIc} KN·m$^{-3/2}$ (lb·in$^{-3/2}$)
4	119	3.9	129	77	14.8	19.9	470	1,860
	(17,260)	(570)	(18,720)	(11,120)	(2,150)	(2,890)	(430)	(1,690)
	[31.0]	[17.4]	[17.7]	[16.5]	[23.1]	[14.7]	[16.5]	[12.5]
7	136	4.3	121	67	13.0	19.2	510	2,050
	(19,740)	(620)	(17,530)	(9,690)	(1,890)	(2,790)	(460)	(1,860)
	[26.0]	[18.3]	[16.9]	[14.9]	[16.8]	[12.5]	[17.6]	[17.5]
12	146	4.5	107	52	10.0	16.8	470	2,070
	(21,190)	(650)	(15,550)	(7,550)	(1,450)	(2,430)	(420)	(1,880)
	[21.8]	[15.8]	[13.1]	[15.1]	[17.5]	[10.2]	[14.2]	[12.9]
18	134	3.4	76	33	7.2	13.5	380	1,840
	(19,370)	(490)	(10,970)	(4,800)	(1,050)	(1,960)	(350)	(1,670)
	[24.6]	[15.3]	[15.8]	[16.1]	[19.0]	[11.0]	[15.7]	[17.7]
Saturated	101	1.9	48	22	4.0	9.0	290	1,380
	(14,660)	(270)	(7,070)	(3,120)	(580)	(1,300)	(260)	(1,250)
	[24.2]	[29.6]	[15.4]	[11.2]	[17.7]	[10.1]	[13.8]	[13.7]

[a] COV is given in brackets.

Moisture content / density - property relationships. - Because density is known to have a significant effect on clear wood properties, empirical models were obtained using both MC and density. Table 7 gives the equations fit to the data for surface models of the following form:

$$\text{Property} = \text{Int} + a(MC) + b(MC)^2 + c(DN) + d(DN)^2 + e(MC)(DN)$$

where Int is the intercept, MC is MC as a percentage, DN is density at 12% MC, and a,b,c,d,e are modeled coefficients.

This model form was chosen because it allows for interaction between MC and specific gravity and fit the observed trends in the data.

TABLE 4. *Average data for modulus of elasticity.*[a]

Moisture content level (%)	Modulus of elasticity (GPa (× 10^6 lb/in^2)) Tension parallel	Tension perpendicular	Modulus of rupture	Compression parallel	Compression perpendicular
4	16.5	0.97	13.8	18.3	0.83
	(2.39)	(0.14)	(2.00)	(2.66)	(0.12)
	[24.9]	[17.9]	[17.7]	[18.3]	[24.1]
7	15.6	1.03	13.1	17.4	0.76
	(2.26)	(0.15)	(1.90)	(2.53)	(0.11)
	[24.5]	[19.6]	[19.6]	[19.9]	[21.4]
12	15.5		13.0	16.5	0.62
	(2.25)	—	(1.88)	(2.40)	(0.09)
	[21.5]		[12.9]	[15.9]	[23.5]
18	12.9	0.55	10.8	11.7	0.41
	(1.87)	(0.08)	(1.56)	(1.70)	(0.06)
	[26.4]	[18.1]	[20.0]	[18.6]	[21.2]
Saturated	11.3	0.28	8.1	7.9	0.21
	(1.64)	(0.04)	(1.18)	(1.15)	(0.03)
	[25.8]	[28.1]	[24.0]	[18.5]	[22.6]

[a] — indicates no data, COV is given in brackets.

DISCUSSION

For all properties, the low MC level specimens behaved in a brittle fashion before failure. The load-deflection plots for 4% and 8% MC indicated little deviation from linearity. The failures that occurred were abrupt and sudden.

Strength and stiffness

The response to MC varied by properties. Ultimate tensile stress (UTS) parallel-and perpendicular-to-the-grain and Mode II stress intensity factor (K_{IIc}) increased as MC decreased, reaching a maximum between 10% and 12% MC. The UTS and (K_{IIc}) values decreased with further drying (Fig. 3-5). Of these, tensile strength parallel-to-grain was the most vari-

TABLE 5. *Moisture content effects on Poisson's ratio.*[a]

Moisture content level (%)	Sample size	Mean		COV (%)		Minimum		Maximum	
		LT	LR	LT	LR	LT	LR	LT	LR
4	41	0.29	0.16	23.4	32.9	0.17	0.08	0.54	0.31
8	39	0.27	0.13	28.9	37.6	0.17	0.02	0.48	0.24
12	38	0.26	0.13	23.1	51.6	0.16	0.00	0.39	0.24
18	38	0.18	0.08	33.3	73.1	0.05	0.01	0.320	0.24
Saturated	40	0.16	0.04	32.1	94.7	0.06	0.00	0.28	0.15

[a] *L is longitudinal; T is tangential; R is radial. The first letter indicates the axis perpendicular to the crack plane, and the second indicates the direction of crack propagation.*

TABLE 6. *Equations for curves fit to strength moisture content data.*[a,b]

	Property = $a(MC)^2 + b(MC) + c$					
	M_p[c]	a	b	c	r^2	MC peak
UTS parallel	23.7	−0.417 (−0.065)	10.51 (1,524)	80.57 (11.685)	0.20	12.6
UTS perpendicular	24.0	−0.016 (−0.0023)	0.33 (0.048)	2.82 (0.410)	0.69	10.2
MOR	22.3	−0.092 (−0.0134)	−1.89 (−0.274)	140.46 (20.371)	0.79	—
UCS parallel	22.1	0.011 (0.0016)	−3.25 (−0.472)	90.17 (13.077)	0.87	—
UCS perpendicular[d]	23.8	— —	−0.555 (−0.081)	16.93 (2.455)	0.78	—
Shear parallel	25.3	−0.0226 (−0.0033)	0.056 (0.008)	19.86 (2.881)	0.81	1.2
K_{Ic} TL	21.5	−0.79 (−0.70)	10.9 (10.0)	447 (407)	0.58	6.9
K_{IIc} TL	23.0	−4.8 (−4.4)	104 (95)	1,505 (1,369)	0.44	10.9
MOE tension parallel	22.4	−8.5 (−1.2)	−45.3 (−6.6)	16,774 (2,433)	0.23	—
MOE tension perpendicular	22.4	−2.06 (−0.3)	17.2 (2.5)	944 (137)	0.82	4.3
MOE bending	22.4	−10.3 (−1.5)	0.9 (0.13)	14,209 (2,061)	0.47	—
MOE compression parallel	21.7	−29.6 (−4.3)	252 (36.5)	17,638 (2,558)	0.70	4.3
MOE compression perpendicular	23.8	—	−33.0 (−5.0)	985 (143)	0.74	—
Poisson's ratio LT	—	−0.00013	−0.00354	0.307	0.36	—
Poisson's ratio LR	—	−0.00019	−0.00076	0.159	0.41	—
Overall average	23.0					

[a] MC is to be entered as a percentage, units for P and K_I and K_{II} are $KN \cdot m^{-3/2}$; Poisson's ratio is unitless; remaining values are MPa (lb/in²).

[b] For parenthetical terms, MC is to be entered as a percentage, units for P and K_I and K_{II} are $lb \cdot in^{-3/2}$; remaining values are ($\times 10^3$ lb/in²).

[c] M_p is an "effective" MC at which further drying has a significant effect on properties, but wetting has little or no noticeable effect.

[d] Linear fit used on data for compression perpendicular-to-grain.

TABLE 7. *Equations for curves fit to strength moisture content and density data.*[a,b]

	Property = Int + a(MC) + b(MC)^2 + c(DN) + d(DN)^2 + e(MC)(DN) (Property = Int + a(MC) + b(MC)^2 + c(SG) + d(SG)^2 + e(MC)(SG))						
	Int	a	b	c	d	e	r^2
UTS parallel	−16.16 (−2.344)	17.364 (2.5184)	−0.422 (−0.06127)	−0.158 (−25.595)	0.000539 (98.009)	−0.01129 (−1.833)	0.47
UTS perpendicular	−4.785 (−0.694)	0.462 (0.067)	−0.0155 (−0.00224)	0.01663 (2.7011)	−0.00000583 (−1.0611)	−0.000262 (−0.0425)	0.80
MOR	1.4717 (0.2134)	4.4049 (0.63886)	−0.1013 (−0.01469)	0.14216 (23.092)	0.000145 (26.384)	−0.010108 (−1.642)	0.90
UCS parallel	−4.0422 (−0.5862)	0.3801 (0.05512)	0.02191 (0.00318)	0.1383 (22.458)	0.0000377 (6.8676)	−0.00661 (−1.074)	0.95
UCS perpendicular[b]	−17.456 (−2.532)	0.2392 (0.0347)	0.001599 (0.000232)	0.07598 (12.341)	−0.0000296 (−5.3852)	−0.001407 (−0.2285)	0.91
Shear parallel	3.0033 (0.4356)	0.8299 (0.12036)	−0.02232 (−0.003238)	0.013746 (2.2329)	0.0000242 (4.4097)	−0.001295 (−0.2104)	0.93
K_{Ic} TL	284.8 (259.2)	21.20 (19.30)	−0.918 (−0.836)	−0.395 (−403.1)	0.00106 (1,210.0)	−0.0113 (−11.52)	0.72
K_{IIc} TL	870.9 (792.6)	110.5 (100.6)	−4.494 (−4.081)	−1.290 (−1,315.1)	0.00408 (4,662.3)	−0.0251 (−25.60)	0.70
MOE tension parallel	9,164.9 (1,329.2)	499.0 (72.37)	−8.723 (−1.265)	−25.256 (−4,102.4)	0.064 (11,647)	−0.9012 (−146.4)	0.52
MOE tension perpendicular	−503.1 (−72.0)	54.7 (7.83)	−1.834 (−0.263)	2.718 (435.8)	−0.000287 (−51.63)	−0.0734 (−11.77)	0.89
MOE bending	−3,790.6 (550)	703.17 (102.0)	−16.554 (−2.401)	−3.183 (−517.1)	0.03139 (5,710.5)	−0.9146 (−148.6)	0.68
MOE compression parallel	−1,444.0 (−209.4)	862.5 (125.1)	−28.047 (−4.068)	24.024 (3,902)	0.014 (22,550)	−1.1011 (−178.9)	0.80
MOE compression perpendicular	−458.01 (−66.4)	25.132 (3.64)	−0.1588 (−0.023)	2.2448 (364.6)	0.000249 (45.32)	−0.08988 (−14.60)	0.87
Poisson's ratio LT	−0.355 (−0.355)	−0.0082 (−0.0082)	−0.000131 (−0.000131)	0.002336 (2.617)	−0.000002037 (−2.556)	0.000008034 (0.0090)	0.37
Poisson's ratio LR	0.284 (0.284)	−0.0056 (−0.0056)	−0.000217 (−0.000217)	−0.00355 (−0.398)	0.000000233 (0.293)	0.000009135 (0.0102)	0.41

[a] Int is the intercept; MC is the moisture content as a percentage; DN is density in kg/m^3 at 12% MC; a, b, c, d, e are modeled coefficients; units for Property for K_I and K_{II} are KN·m$^{-3/2}$; Poisson's ratio is unitless; values remaining are in MPa.

[b] For the parenthetical term, Int is the intercept; MC is the moisture content as a percentage; SG is the specific gravity based on ovendry weight and volume at 12% MC; a, b, c, d, e are modeled coefficients; units for Property for K_I and K_{II} are lb·in$^{-3/2}$; Poisson's ratio is unitless; values remaining are in (×10^3 lb/in^2).

able. However, the observed trends in UTS with changing MC were consistent, over the majority of percentiles, with trends reported in the literature for clear wood and lumber (Green and Kretschmann 1994).

Mode I stress intensity factor (K_{Ic}), shear stress parallel-to-grain, modulus of elasticity (MOE) in tension parallel- and perpendicular-to-grain, and MOE in compression parallel-to-grain increased from green to about 6% MC, then increased little, if at all, with additional drying (Fig. 6–10). Bending, compression parallel- and perpendicular-to-grain stress, and MOE in bending and compression perpendicular-to-grain appeared to increase continually with drying from green to 4% MC (Fig. 11-15). A summary of the changes in average strength and stiffness values relative to 12% MC is given in Table 8.

Poisson's ratio

Both LT (deformation in tangential direction when longitudinal load is applied) and LR (deformation in radial direction when longi-

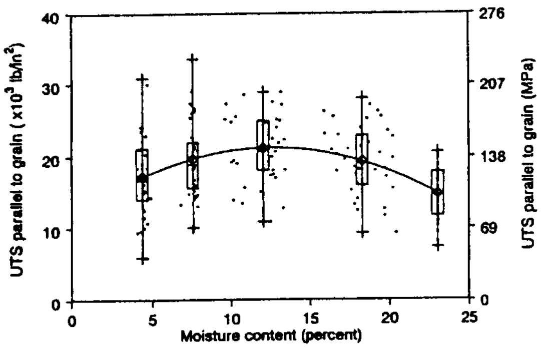

FIG. 3. Relationship of ultimate tensile stress (UTS) parallel-to-grain and moisure content.

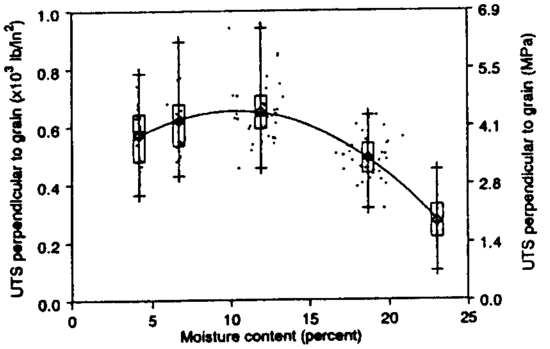

FIG. 4. Relationship of ultimate tensile stress (UTS) perpendicular-to-grain and moisture content.

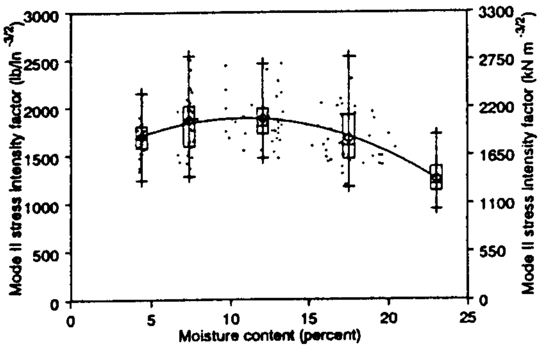

FIG. 5. Relationship of Mode II stress intensity factor and moisture content.

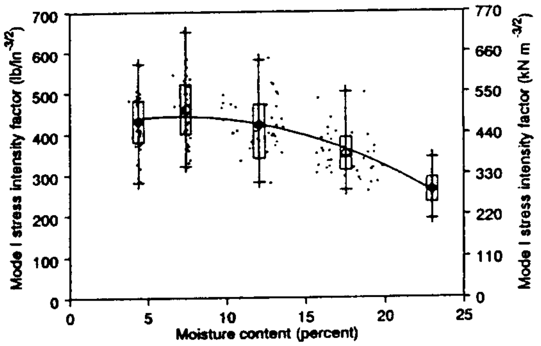

FIG. 6. Relationship of Mode I stress intensity factor and moisture content.

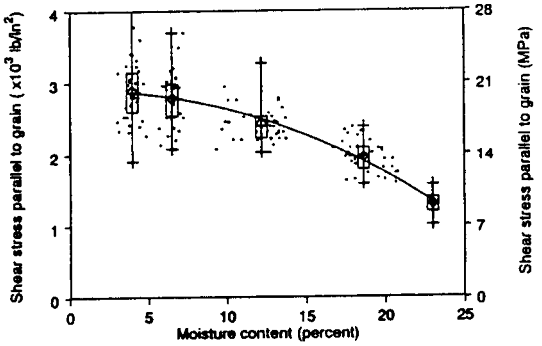

FIG. 7. Relationship of shear stress parallel-to-grain and moisture content.

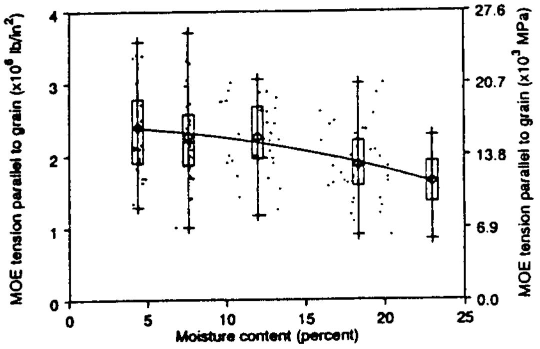

FIG. 8. Relationship of modulus of elasticity (MOE) in tension parallel-to-grain and moisture content.

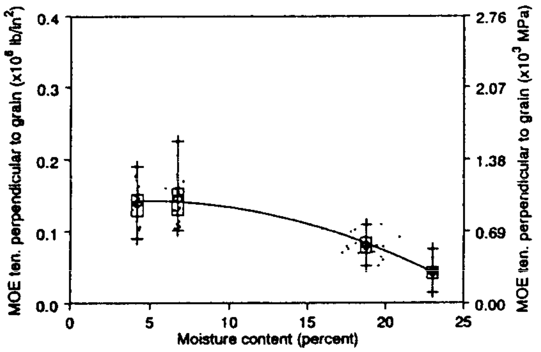

FIG. 9. Relationship of modulus of elasticity (MOE) in tension perpendicular-to-grain and moisture content.

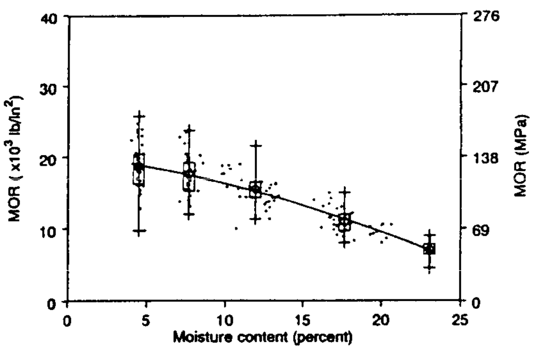

FIG. 11. Relationship of bending modulus of rupture (MOR) and moisture content.

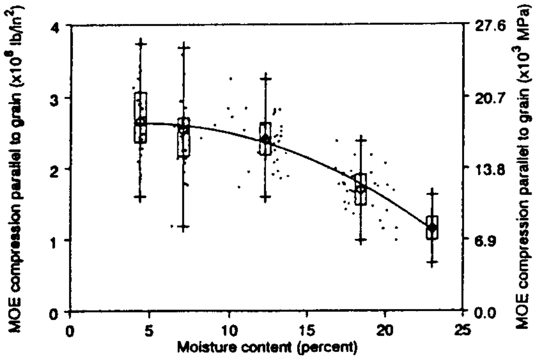

FIG. 10. Relationship of modulus of elasticity (MOE) in compression parallel-to-grain and moisture content.

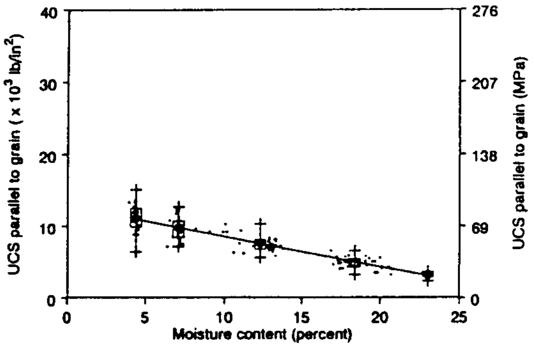

FIG. 12. Relationship of ultimate compressive stress (UCS) parallel-to-grain and moisture content.

TABLE 8. *Percentage difference of strength level mean relative to 12% moisture content.*

	Difference (%)							
Property/ moisture content	Tension parallel	Tension perpendicular	MOR	Compression parallel	Compression perpendicular	Shear parallel	K_{Ic}	K_{IIc}
Strength								
4%	−19	−12	20	47	48	19	1	−10
8%	−7	−5	13	28	30	15	8	1
18%	−9	−25	−29	−36	−27	−20	−18	−11
Saturated	−31	−59	−55	−59	−60	−47	−39	−34
Modulus of elasticity								
4%	6	—	6	11	43	—	—	—
8%	0	—	1	5	29	—	—	—
18%	−17	—	−17	−30	−30	—	—	—
Saturated	−27	—	−37	−52	−63	—	—	—

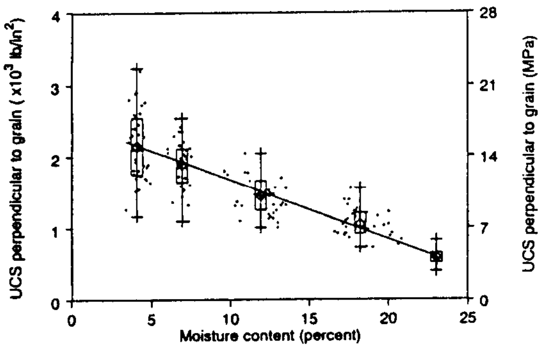

FIG. 13. Relationship of ultimate compressive stress (UCS) perpendicular-to-grain and moisture content.

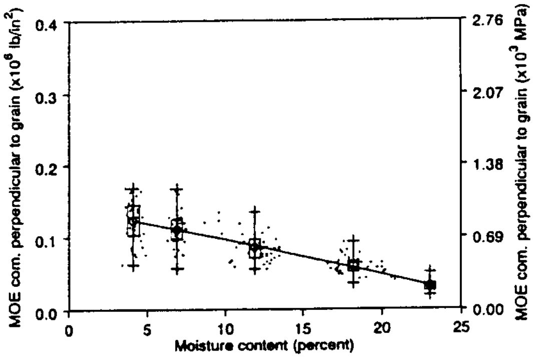

FIG. 15. Relationship of modulus of elasticity (MOE) in compression perpendicular-to-the-grain and moisture content.

tudinal load is applied) Poisson's ratio increased with decreasing MC from green to 4% MC (Figs. 16, 17). For this material, the average LT and LR Poisson's ratios were 0.26 and 0.13 at 12% MC, respectively. Relative to the value at 12% MC, the change in modeled LT Poisson's ratio was about – 36% when green, – 18% at 18% MC, 12% at 7% MC, and 18% at 4% MC. Relative to the value at 12% MC, the change in modeled LR Poisson's ratio was about – 67% when green, – 32% at 18% MC, 18% at 7% MC, and 25% at 4% MC. For 4%, 7%, 12%, and 18% MC, LR Poisson's ratio was consistently about half that of the value for LT.

Moisture content-density interactions

The interactions between density and changes in MC explain a large portion of the

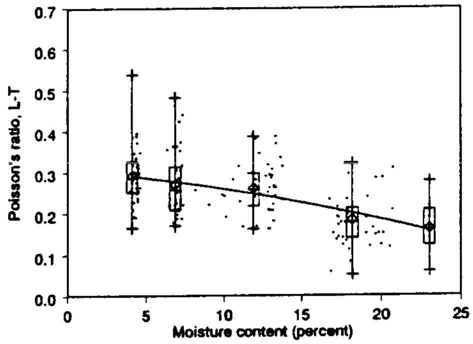

FIG. 16. Relationship of Poissons's ratio in the longitudinal-tangential (LT) direction.

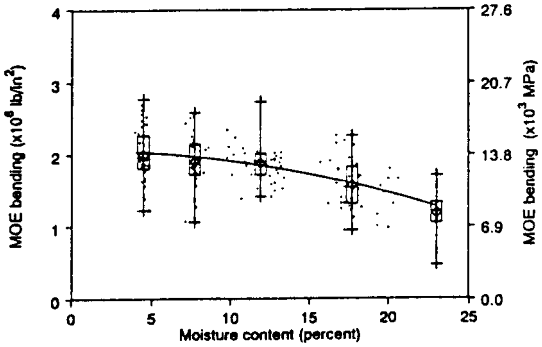

FIG. 14. Relationship of modulus of elasticity (MOE) in bending and moisture content.

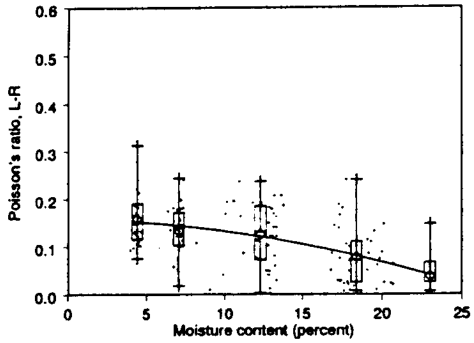

FIG. 17. Relationship of Poisson's ratio in the longitudinal-radial (LR) direction.

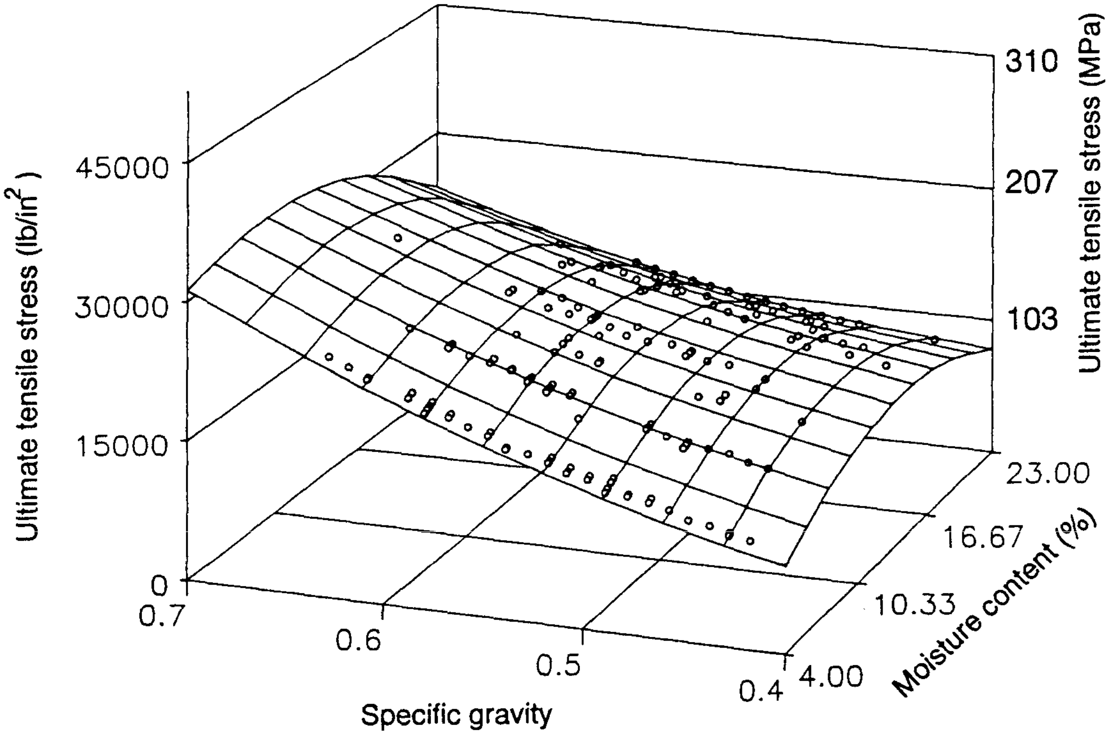

FIG. 18. Response surface for tension parallel-to-grain stress. Dots on surface represent x-y location of test data on surface.

observed variability in properties. The r^2 values of the curve fits ranged from a low of 0.47 to a high of 0.95. A few selected response surfaces for tension and compression parallel-to-grain, bending, and shear strength and compression parallel-to-grain MOE are shown in Figs. 18-22. The dots on the response surfaces represent the density and MC location of individual data points. The tension parallel-to-the-grain surface indicates a consistent peak at all levels of density distribution. This trend follows that which was suggested in studies of dimension lumber (Green et al. 1990, Fig. 1). The compression surface indicates that specimens with high density values were more sensitive to changes in MC than specimens with low density values. As expected, the bending MOR surface is a combination of the tension and compression surfaces. The shear strength surface also indicates greater sensitivity to the MC changes in specimens with high density values. Finally, the compression parallel-to-grain surface had a shifting peak strength. Illustrations of the remaining surfaces are available upon request.

It would appear that MC levels of about 6% and 12% may be critical to understanding wood moisture-property relationships in clear wood and therefore influence the fundamental relationships controlling the tensile strength of lumber (Green et al. 1990). From observations of the failure process and trends in the results presented for southern pine, it appears that some fundamental degradation mechanism, or combination of mechanisms, is involved when properties are evaluated at lower MC levels. Molecular considerations and micromechanical failure mechanisms in the cell wall may offer a possible explanation of these mechanisms.

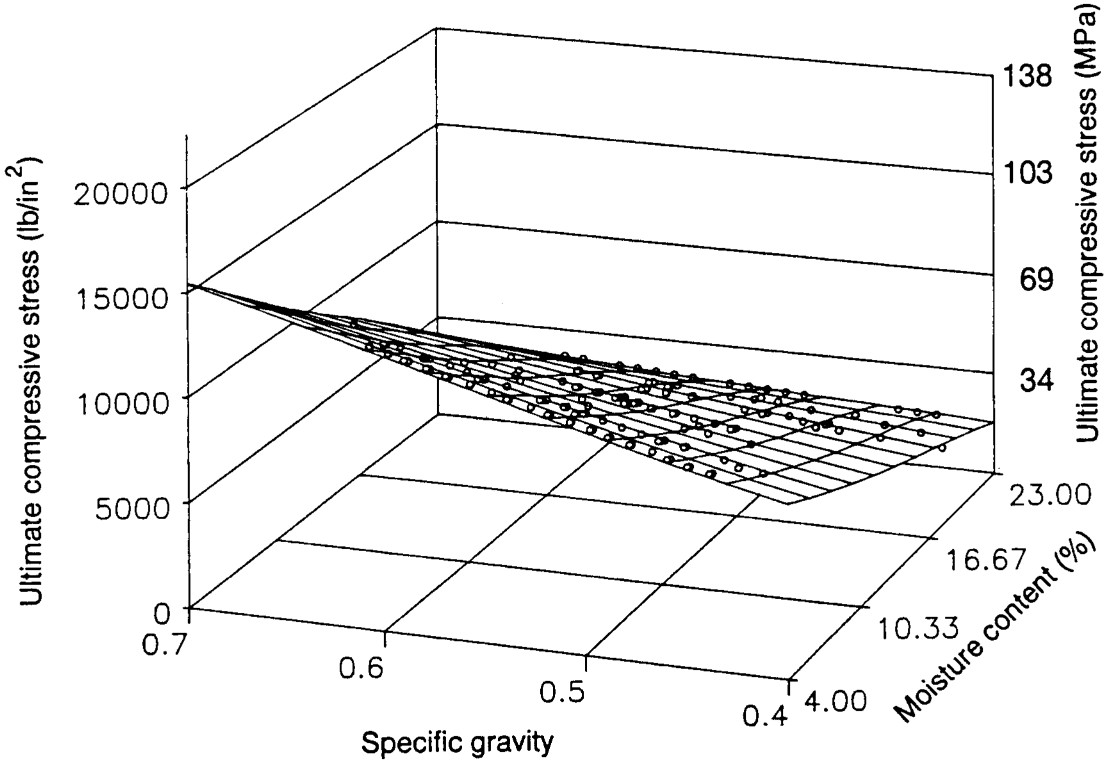

FIG. 19. Response surface for compression parallel-to-grain stress. Dots on surface represent x-y location of test data on surface.

Molecular considerations

Several theories postulate that water molecules in the cell wall are held on preexisting internal surfaces by hydrogen bonds (Skaar 1972; Hartley and Kamke 1992). The most popular of these theories is that of Brunauer, Emmett, and Teller (the BET theory). The BET theory considers that this sorbed water exists in one to several layers. At room temperature, the MC corresponding to complete monomolecular sorption is about 6%. As the monolayer of water is driven off, there is a chance that some covalent bonds are broken and the wood is degraded (Stamm 1964). Thus, it was not surprising that some properties in our study began to behave differently at less than about 6% MC.

Research on the effect of MC on the mechanical properties of paper provides additional insight into fundamental property-MC mechanisms. A theory developed by Nissan (1977) relates the reduction in elastic modulus with increasing MC to a reduction in the effective number of hydrogen bonds available to maintain the saturated integrity of the cell wall (Caulfield 1990). Theoretically, Nissan's work suggests a constant relationship between the change in MOE with changing MC.

$$K = \frac{-d[\ln(\mathrm{MOE})]}{d(\mathrm{MC})}$$

Nissan combined the idea of hydrogen-bond-dominated solids with the cluster integral concept of water to explain the cooperative bond breaking. Limited experimental results indicated that the value of K at MC levels less than about 5% is much different than at greater than 5% (Nissan 1977). Caulfield also noted that the tensile strength of paper reaches a maximum at an RH from 30% to 50%. Thus, the

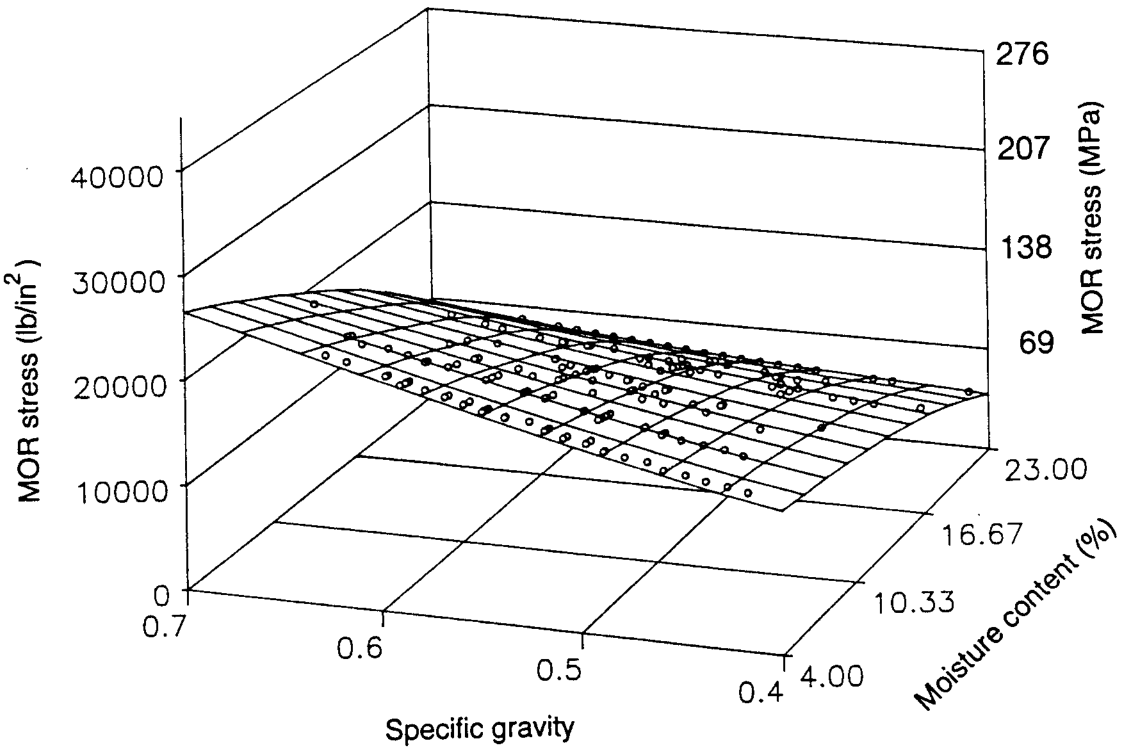

FIG. 20. Response surface for modulus of rupture. Dots on surface represent x-y location of test data on surface.

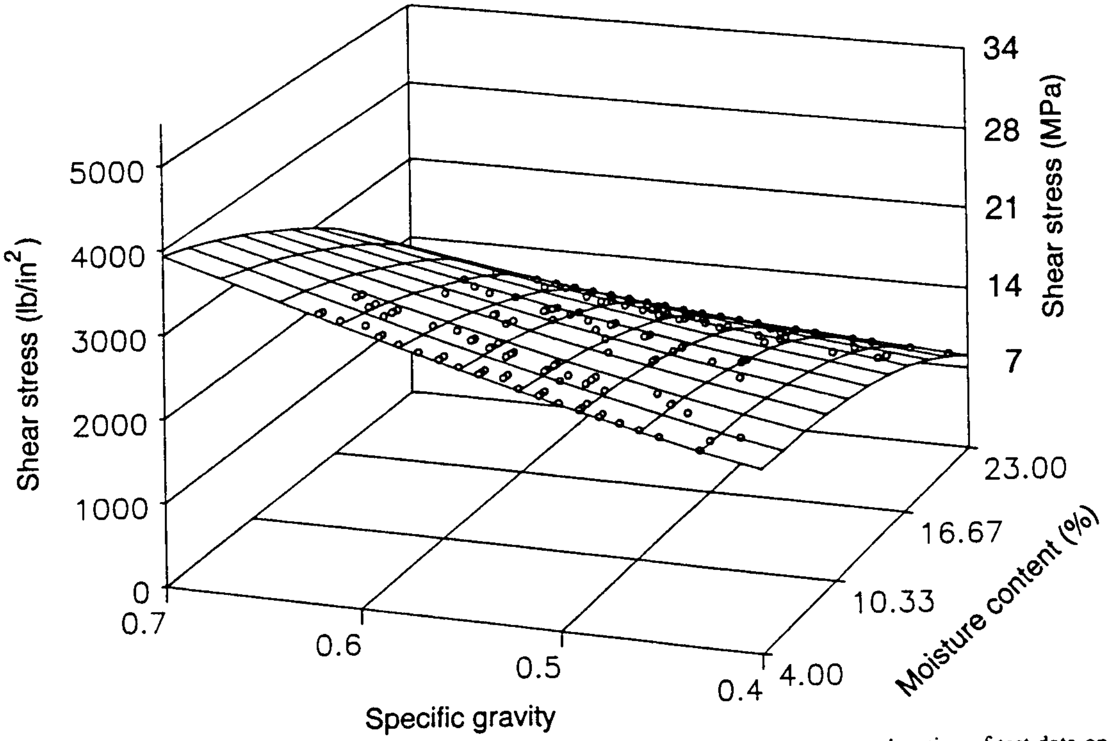

FIG. 21. Response surface for shear parallel-to-grain stress. Dots on surface represent x-y location of test data on surface.

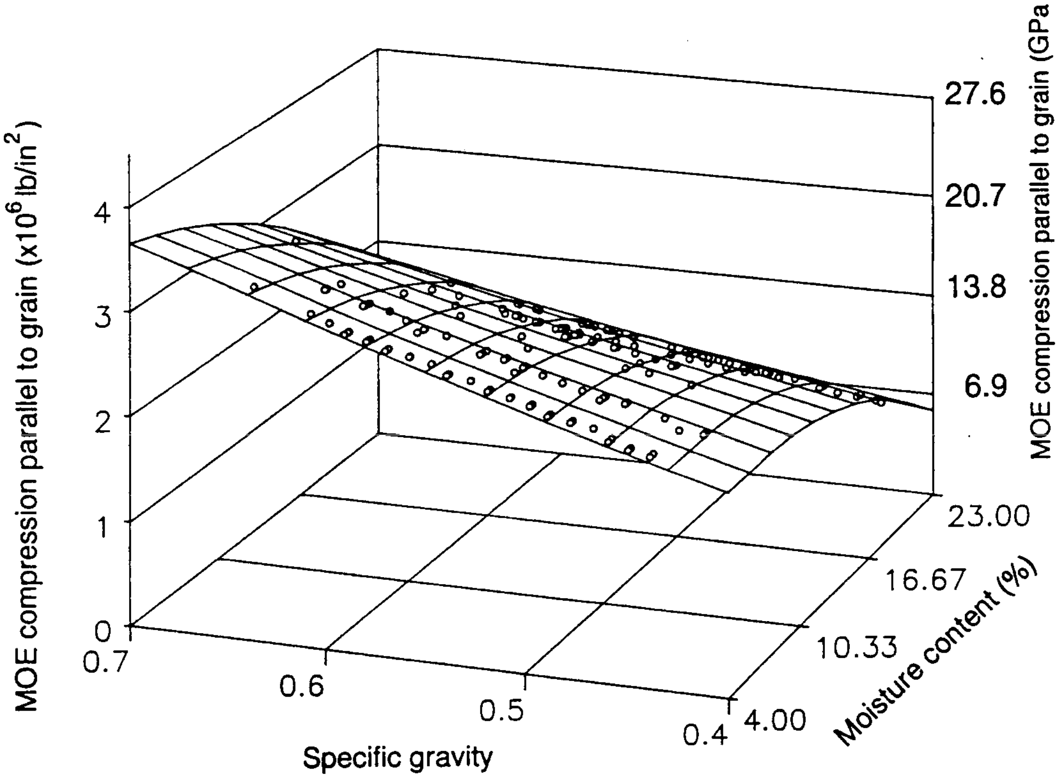

FIG. 22. Response surface for compression parallel-to-grain modulus of elasticity (MOE). Dots on surface represent x-y location of test data on surface.

tensile strength of paper would be maximum at 6% to 9% MC.

Micromechanical failure mechanisms

The previous discussion used theories of water bonding to understand potential changes in property-MC relations at about 6% MC. However, this approach does not seem sufficient for UTS parallel-to-grain. First, UTS involves stresses generally parallel to the axis of the cellulose chain. Second, the UTS-MC relationship peaks at about 12% MC, not 6% MC. However, failure mechanisms in the cell wall may provide additional insight. A thorough discussion of micromechanical failure mechanisms in softwood species is given by Mark (1967). Mark documents that initial failure in the cell wall is most likely to occur in the S_1 layer or at the S_1/S_2 interface. Further, he hypothesizes that interlaminar shear stresses are the most likely cause of failure. Following this initial failure, he calculates a redistribution of stresses with final failure in the S_2 layer. We note that K_{IIcTL} (Mode II stress intensity factor), which characterizes resistance to the formation of cracks as a result of shearing stresses, is maximum at about 12% MC. Thus, we hypothesize that shearing stresses at the microscopic level could help to account for the maximum value of tensile strength parallel-to-grain observed at about 12% MC.

CONCLUSIONS

From the results of our study on the effect of moisture content (MC) on clear wood properties in southern pine, we conclude the following

- Ultimate tensile stress (UTS) parallel-and perpendicular-to-the-grain increases as MC decreases, reaching a maximum between 10% and 12% MC. The UTS values decrease with additional drying.

- Modulus of elasticity (MOE) in tension parallel- and perpendicular-to-grain, MOE in compression parallel-to-grain, and shear strength parallel-to-grain increase from green to about 6% MC, then increase slightly with additional drying.
- Compression strength parallel- and perpendicular-to-grain, bending strength, and MOE in bending and compression perpendicular-to-grain appear to increase with drying, from green to 4% MC.
- The MC above which properties cease to decrease with increasing MC (M_p) is remarkably constant across properties and averages 23%.
- The critical levels in the MC-property relationship occur at about 6 and 12% MC, depending upon property. This behavior can be understood by considering molecular forces and wood macrostructure.

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