THE IMMEDIATE EFFECT OF TEMPERATURE ON THE MODULUS OF ELASTICITY OF GREEN AND DRY LUMBER[1]

*David W. Green**†

Supervisory Research Engineer, Emeritus

James W. Evans

Supervisory Mathematical Statistician
USDA Forest Service
Forest Products Laboratory
One Gifford Pinchot Drive
Madison, WI 53726

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Abstract. This study evaluated the immediate (reversible) effect of temperature on flexural modulus of elasticity (MOE) of green and dry nominal 2x4 (standard 38 by 89 mm) structural lumber from 66 to −26°C. For lumber at 4 and 12% moisture content (MC), a linear relationship was used to relate the increase in MOE to decreases in temperature. For green lumber, MOE also increased with decreasing temperature. A segmented linear regression was developed to describe the change in MOE of green lumber for 66 to −18°C. The slope of this relationship was steeper below 0°C than above. The actual MC of green lumber was not a factor above −18°C. Below this temperature, the increase in MOE with decreasing temperature was a function of both actual green MC and temperature. We discuss factors that cause this behavior in green wood at low temperatures and the use of an empirical model for describing the MOE−temperature relationship as a function of MC for frozen green lumber.

Keywords: Dry, green, MOE, moisture content, temperature change, lumber.

INTRODUCTION

The need to adjust modulus of elasticity (MOE) in bending for the effect of temperature may arise in determining lumber properties for both visually- and mechanically-graded lumber. For example, in bending tests of visually-graded lumber conducted in the field using portable equipment (Shelley 1989), wood temperatures ranged from about −18 to 32°C. Such test results must be corrected to room temperature to obtain meaningful results. Also, sorting of machine stress-rated (MSR) lumber could be done on lumber at an average temperature of 50 to 55°C if still hot from kiln drying, or at temperatures below freezing if the lumber has been in the mill yard in the winter. Correcting machine threshold settings for the actual temperature of the lumber can improve grade yield compared with the historical practice of making conservative assumptions from assumed temperatures.

Two types of temperature effects are traditionally considered for wood properties: immediate effects and permanent effects (FPL 1999). As wood is cooled below normal temperatures, its mechanical properties tend to increase. Conversely, when wood is heated, its mechanical properties decrease. The magnitude of the change depends upon the MC of the wood, and when wood is heated, on the duration of temperature exposure. The change in property that occurs when wood is quickly heated or cooled, and then tested at the altered temperature is termed the immediate, or reversible effect, that is, the property will return to the original value when the wood temperature is returned to its original value. The immediate effect is the result

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* Corresponding author: levangreen@hughes.net
† SWST member

of a transitory change in the internal energy level of the wood. Permanent or irreversible loss in properties may also occur when wood is heated to elevated temperatures. This permanent effect is one of thermal degradation of wood substance, which results in weight loss and lowering of properties when wood is tested at room temperature. The permanent effect of temperature on the flexural properties of solid-sawn and composite lumber products is the subject of an ongoing study (Green et al 2003, 2005; Green and Evans 2008).

The objectives of this study were to determine the immediate effect of temperature on MOE of structural lumber within the temperature range of −26 to 66°C, and to develop analytical models to predict this change. This paper extends previously published results to lumber with below 12% MC (Green et al 1999). Mechanical properties of lumber are typically based on the dimensions of the lumber at time of test. Since analytical models developed using such data already incorporate change in dimension into predicted properties, this report does not directly consider the effect of MC and temperature on member dimensions (Green 1981; Green and Evans 2003).

PROCEDURES

Data Sets

Table 1 summarizes the six data sets used to develop analytical adjustment procedures for MOE of dry lumber ("dry MOE") and the three data sets used for MOE of green lumber ("green MOE"). With one exception, the 2 × 4 specimens for each data set were moved from one conditioning chamber to another. Thus, all specimens were exposed to all temperatures. Data sets 1, 2, and 6 were from our original study (Barrett et al 1989) and data sets 3, 4, 5, and 7 from our 1999 study (Green et al 1999). The southern pine lumber for data sets 8 and 9 was purchased for the current study.

The Douglas-fir lumber (data set 1) was taken from existing supplies at the Forest Products Laboratory (FPL). This lumber had been graded as No. 1 for strength reductions (eg knots) in the middle 610 mm of the span. Because this was not typical No. 1 lumber, its grade is called "special." The southern pine lumber for data sets 2 and 6 was commercially graded No. 2 Dense (2D) and obtained from a supplier in Madison, WI. The southern pine lumber for data set 3 was commercially graded in three MSR grades (1650f–1.5E, 2100f–1.8E, and 2400f–2.0E),[2] and was taken from available inventory at FPL. Data sets 4 and 5 consisted of two grades of Spruce–Pine–Fir MSR lumber, 1650f–1.5E and 2100f–1.8E. Data set 7 was western hemlock that was commercially graded at a mill in southeast Alaska and contained an approximately equal mixture of No. 3, No. 2, and Select Structural lumber. Data sets 8 and 9 consisted of approximately equal numbers (about 18 pieces each) of No. 2 and Select Structural 2 × 4s determined by a Southern Pine Inspection Bureau quality supervisor as "on-grade" for strength-reducing reasons. This lumber was obtained from a mill in northern Alabama, wrapped in plastic, and shipped to FPL. The lumber in data set 9 is the same as that of data set 8 except that the lumber was conditioned to the lower MC. The sample sizes differ because seven pieces were sacrificed to estimate the actual MC of the green lumber.

The lumber for data sets 1, 2, and 3 was initially equilibrated at room temperature and 65% relative humidity (RH), which corresponds to an anticipated 12% MC. For these three data sets, MOE was determined at one temperature and then the specimens were taken to another chamber for conditioning to different temperature level. Thus, all MOE measurements were taken from the same specimens at all temperatures. In

[2] For MSR lumber, the numeral accompanied by the letter f indicates the allowable bending strength in pounds per square inch and that by the letter E the allowable MOE in millions of pounds per square inch. SI units are not legally assigned these grades in the United States, but an approximate conversion for 1650f–1.5E, 2100f–1.8E, and 2400f-2.0E would be 11.4f–10.3E, 14.5f–12.4E, and 16.5f–13.8E (MPa and GPa).

TABLE 1. *Effect of temperature on modulus of elasticity of lumber in bending.*

Data set	Species[a]	Grade	n	MC (%)	Temperature (°C)	Modulus of elasticity (GPa) Mean	SD
1	DF	Special	73	10.2	−23	11.07	2.01
					2	10.55	2.06
					6	10.25	2.03
					23	10.19	2.06
					32	9.89	1.88
2	SP	No. 2D	50	12.4	−23	11.49	2.21
					−4	11.12	2.45
					2	11.03	2.49
					6	10.62	2.08
					23	10.38	2.35
					32	10.37	2.41
3	SP	MSR	30	12.6	−26	14.16	3.83
					−18	14.03	3.56
					2	13.75	3.53
					24	13.22	3.34
					42	13.08	3.32
					66	12.13	3.33
4	SPF	1650f	31	11.0	20	10.83	1.24
					66	9.67	1.25
5	SPF	2100f	30	11.5	20	12.88	1.14
					66	11.53	0.94
6	SP	No. 2D	50	145	−23	13.99	2.36
					−4	9.18	2.03
					2	9.09	2.17
					6	8.67	1.99
					23	8.28	1.85
					32	7.94	1.89
7	WH	No. 3 +	22	53	−26	14.96	2.05
					−23	13.29	1.95
					−18	12.86	1.96
					2	11.31	1.92
					23	10.62	1.85
					42	10.08	1.84
					66	8.93	1.85
8	SP	SS & No. 2	36	104	−26	13.70	2.38
					−23	13.04	2.59
					−18	11.22	2.87
					2	9.29	2.51
					23	8.98	2.32
					42	8.58	2.40
					66	7.85	2.31
9	SP	SS & No. 2	29	3.8	−18	14.73	3.76
					2	14.46	3.70
					23	14.22	3.76
					66	13.66	3.52

[a] DF is Douglas-fir, SP is southern pine, SPF is Spruce-Pine-Fir, and WH is Western Hemlock

each temperature chamber, the specimens were wrapped in plastic to prevent possible drying. A moisture meter was used to verify the stability of MC values. All lumber was tested at a room temperature of approximately 23°C. To minimize exposure to room temperature, each specimen was placed in an individual insulated box while in the conditioning chamber. The box was then carried to the testing machine and the specimen removed for testing.

The lumber for data sets 1 and 2 was tested on edge in third-point bending according to ASTM D4761-05 (2007). The specimen span-to-depth ratio was 17:1. To minimize exposure to room temperature, testing was done at a rate of crosshead motion of 51 mm/min. The MOE of the data set 3 lumber was determined by transverse vibration (D) over the full length of the specimens (ASTM D6874-03 2007). The testing equipment was set up just outside the conditioning room and the lumber brought out one piece at a time to minimize exposure to room temperature.

For data sets 4 and 5 prior to testing, each grade of lumber was divided into two equal groups based on ranked MOE values at room temperature (hereafter called matched specimens). This procedure was followed because the specimens of this data set were part of a broader study on the strength and stiffness of lumber exposed to high temperatures for extended periods. As with the lumber for data set 3, MOE values for data sets 4 and 5 were determined by transverse vibration using equipment set up just outside the 66°C–75% RH conditioning chamber. Following testing, lumber oven-dry MC was determined using ASTM D4442-92 (2007).

After testing in the dry condition, the lumber for data set 2 was placed in a treating cylinder that was filled with water at 23°C. A vacuum at 7 kPa was applied for 1 h, followed by 861 kPa pressure for 2 h. These soaked specimens were thereafter labeled as data set 6. The lumber was tested in static bending as described for data set 2.

The lumber for data sets 7 and 8 was soaked in water overnight before each successive temperature exposure to ensure that no surface drying had occurred. As with the dry specimens, the lumber was wrapped in plastic during exposure to minimize drying, and the test machine was set up just outside the temperature chamber to minimize exposure of specimens to room temperature during the test. MOE was determined by transverse vibration; the lumber was supported at the ends of 3-m-long pieces. MC was determined prior to the first temperature exposure from sections available when the lumber was cut from the original 4.3-m length to the final 3-m length.

The lumber of data set 9 is the same lumber as that of data set 8, except that four pieces of lumber in data set 8 were cut to obtain actual green MCs, and three additional pieces could not be tested due to warp after drying to 4% MC. After testing in the green condition, the lumber was placed in a conditioning room and equilibrated to approximately 4% MC. The lumber was then moved to successive RH rooms as for the green lumber. Experimental procedures for data set 9 were the same as those used for data sets 1 and 2.

Analytical Model

In previous work on modeling the effect of temperature on flexural properties, we evaluated two alternatives: analytical models based on the absolute value of MOE at the test temperature and analytical models based on the change in property relative to a base temperature (Barrett et al 1989). This work established that a model based on the change in property relative to a base temperature would tend to minimize differences in prediction across percentile levels of the property distribution. Thus, the relationship between MOE and temperature is described in terms of the percentage of change in MOE relative to MOE at room temperature. The percentage of change in MOE is defined as

$$\Delta\text{MOE}\ (\%) = 100[(E_T - E_o)/E_o] \qquad (1)$$

where E_T is MOE at temperature T and E_o is MOE at 23°C. The model of Eq (1) was also of the same form as used in our previous study (Green et al 1999).

RESULTS

Estimation of Dry MOE

Figure 1 summarizes the data for dry lumber at approximately 12% MC presented in Table 1 (data sets 1–5). A box plot of the data at a given

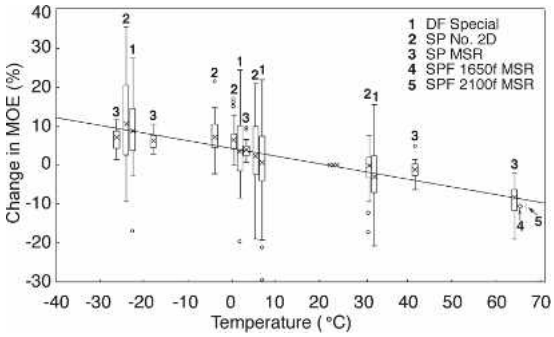

FIGURE 1. Effect of temperature on change in MOE of Douglas-fir, southern pine, and Spruce–Pine–Fir (SPF) solid-sawn lumber at 12% moisture content.

temperature is shown for each data set. The box plot shows the mean value (x), middle 50% (25th to 75th percentile) (box), nominal range (error bars), and an occasional outlying point or outlier (circle). When more than one data set was tested at a given temperature, the two sets are slightly offset for clarity. A linear regression provided the best fit to the dry MOE data:

$$\Delta\text{MOE}\ (\%) = 4.3104 - 0.1994T_{\text{C}} \qquad (2)$$

where T_{C} is °C. The regression equation has a coefficient of determination, r^2, of 0.93. Figure 2 shows a 95% confidence interval on MOE mean values predicted from the regression equation.

Figure 3 shows the change in MOE with change in temperature for data set 9 at 4% MC. As with lumber at 12% MC, a linear regression provided the best fit to the data over the entire temperature range. There is no inflection point in the slope at about 0°C. The regression fit to the mean values of the data is given in Eq (3).

$$\Delta\text{MOE}\ (\%) = 2.2924 - 0.0926T_{\text{c}} \qquad (3)$$

Equation (3) has an r^2 of 0.998. The 95% confidence intervals on Eq (3) are shown in Fig 4. As expected, the slope of the relationship at 4% MC (Eq (3)) is less than that at 12% (Eq (2)), thus indicating that the MOE of lumber is less sensitive to change in temperature at 4% than at 12% MC. At 0°C, Eq (3) would predict a 2.3% increase in MOE and at 66°C, a 3.8% decrease. The corresponding changes at 12% MC (Eq (2)) are a 4.3% increase to 0°C and an 8.8% loss to 66°C.

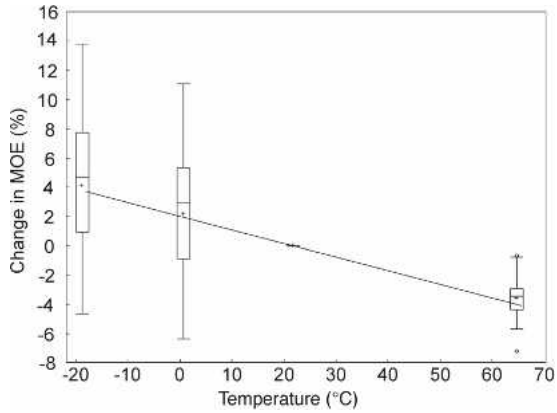

FIGURE 3. Effect of temperature on change in MOE of southern pine lumber at 4% moisture content.

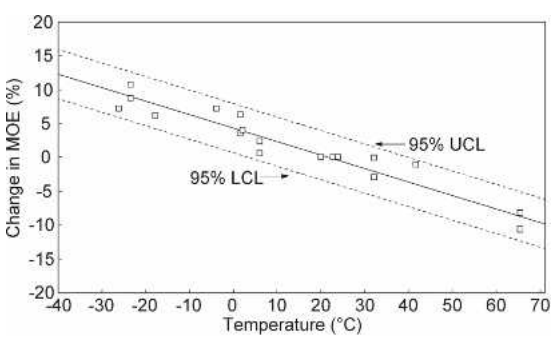

FIGURE 2. Modeling of effect of temperature on MOE of solid-sawn lumber at 12% moisture content. LCL and UCL are lower and upper confidence limits, respectively.

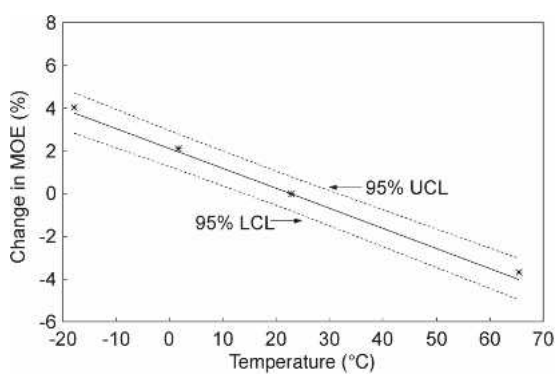

FIGURE 4. Modeling of effect of temperature on MOE of southern pine lumber at 4% moisture content.

Estimation of Green MOE

Figure 5 summarizes the green lumber data of data sets 6, 7, and 8 presented in Table 1. As expected, a change in the slope of the temperature–MOE relationship occurred at about the freezing point of water. A segmented linear regression provided the best fit to the green data (Eqs (4a and 4b)). As will be discussed in the Additional Considerations section to follow, the data in data sets 7 and 8 at −26°C and data set 8 at −23°C were not used in developing Eqs (4a and 4b).

$$\text{If } T \geq 0°\text{C}, \Delta\text{MOE (\%)} = 7.3837 - 0.3227T_C \quad (4a)$$

$$\text{If } T \leq 0°\text{C}, \Delta\text{MOE (\%)} = 7.3838 - 0.8241T_C \quad (4b)$$

For a segmented regression, an r^2 value is not appropriate, since each segment would have a different r^2 value, and it is further complicated because we are regressing a ratio of MOE values vs temperature. The standard deviation about the regression line is 1.2%. When cooled to 0°C, Eqs (4a and 4b) predict a 7.4% increase in MOE, and when heated to 66°C there would be a 47% increase. As expected, the MOE of green lumber is much more sensitive to change in temperature than is that of dry lumber.

Estimation of MOE at Other Moisture Content Levels

In our previous paper (Green et al 1999), we developed equations for predicting the effect of temperature on percentage of change in MOE for MC ranging from 12% to an assumed green MC of 23%. This was done by linear interpolation between the properties predicted by Eqs (2) and (4a and 4b). We now want to extend these equations to lower MC levels by linear interpolation between the results predicted by Eqs (2) and (3). First, we must choose a standard reference temperature.

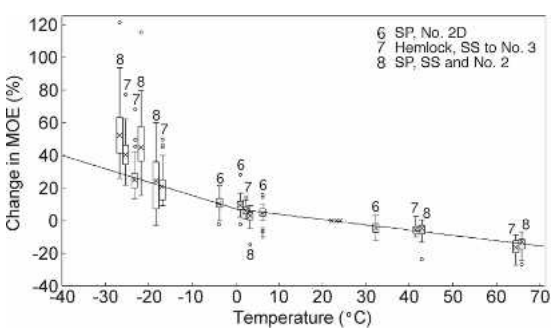

FIGURE 5. Effect of temperature on change in MOE of green southern pine and western hemlock lumber.

In our previous study, individual data sets were tested at periods that sometimes differed by several years. Thus, the temperature considered to be "room" temperature varied slightly from data set to data set. Equation (2) yields a zero change in MOE at a room temperature of about 24.8°C and Eq (4) at 22.9°C. These two temperatures were close enough that in the previous paper we ignored these differences in our overall model. To achieve 4% MC in the latest data required a different conditioning room and thus yet another "room" temperature. To eliminate these variations in room temperature, we decided to adjust all equations to predict zero percentage of change in MOE at 23°C, as recommended in ASTM D1990-00 (2007). This made little change in the results predicted by Eqs (2), (3), and (4a and 4b), but it did change the regression coefficients slightly. The new equations are as follows:

$$\text{At 4\% MC}, \Delta\text{MOE (\%)} = 2.1297 - 0.09351T_C \quad (5)$$

$$\text{At 12\% MC}, \Delta\text{MOE (\%)} = 4.4971 - 0.19746T_C \quad (6)$$

For green lumber

$$\text{If } T \geq 0°\text{C}, \Delta\text{MOE (\%)} = 7.3463 - 0.3225T_C \quad (7a)$$

$$\text{If } T < 0°\text{C}, \Delta\text{MOE (\%)} = 7.3478 - 0.8259T_C \quad (7b)$$

Linear interpolation between Eqs (5), (6), and (7a and 7b) can now be used to develop equations at intermediate MC levels. In general, the form of these equations is:

$$\text{For 4} - \text{12\% MC}, \Delta\text{MOE (\%)} = [(\text{E4} - \text{E12})((12 - \text{MC})/8)] + \text{E12} \quad (8)$$

For above 12% MC, ΔMOE (%) =

$$[(E23 - E12)((MC - 12)/11)] + E12 \quad (9)$$

where EN refers to change in MOE at either 4, 12, or 23%.

The equations generated from Eqs (8) and (9) are given in Table 2 and are plotted in Fig 6. These equations can be used for dry lumber within the temperature range for which we had data, 66 to −26°C. As will be discussed, these equations should not be applied to green lumber if the temperature is below −18°C. This is indicated on the figure for the 23% line by a dotted line below −18°C. Lumber with MC ≥23% is assumed to be green (Green and Evans 1989; Kretschmann and Green 1996).

ADDITIONAL CONSIDERATIONS

Effect of Moisture Content on Green MOE at Low Temperatures

Mishiro and Asano (1984) found that MC could affect the change in MOE for 10 × 5 x 13-mm clear spruce specimens below 0°C that were supersaturated with water (Fig 7). In our previous paper (Green et al 1999), we demonstrated this effect with some of our data. First, observe the width of the error bars for the data presented in Fig 5, and remember that all pieces of lumber in a given data set were exposed to all temperatures. In general, the variability of the data is reasonably constant from 66 to 0°C. Below freezing, the variability generally increases with decreasing temperature. To about −18°C, the increase in variability does not significantly affect the mean trend between change in MOE and temperature. However, for hemlock at −26°C and southern pine at −26 and −23°C, the mean trend for data sets 7 and 8 was above the general trend line. The sudden rise in hemlock MOE at −26°C compared with that in southern pine MOE at −23°C was not attributable to species. Rather, this difference was the result of the lower green MC of hemlock (53%) compared with that of southern pine (104%) (Table 1). Average MC was probably lower in the hemlock because this wood came from Alaska and contained a higher percentage of lower MC heartwood than did the southern pine.

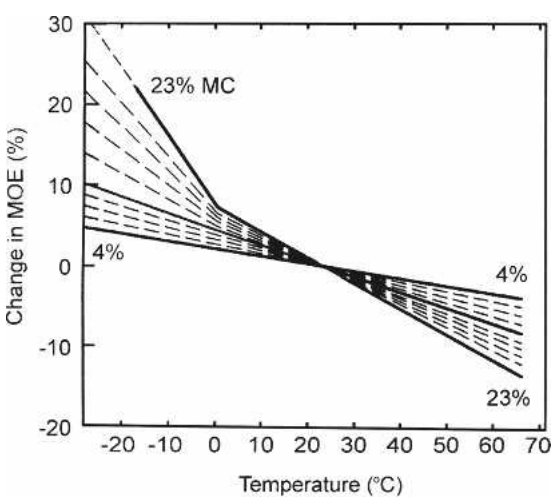

FIGURE 6. Predicted relationship between change in MOE and temperature at various moisture content (MC) levels.

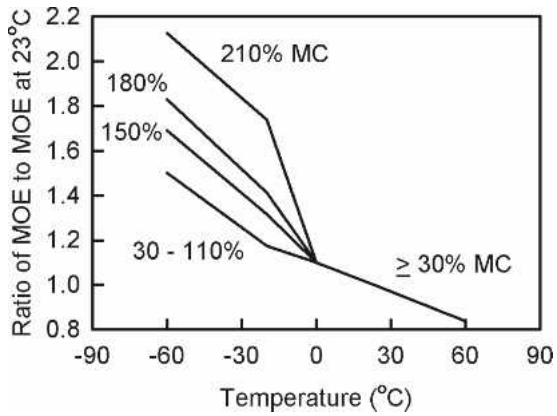

FIGURE 7. Effect of temperature on MOE of green spruce at various moisture contents (MC) (Mishiro and Asano 1984.

Figure 8 further illustrates the relationship between green MC and change in MOE at very cold temperatures. Here, the change in MOE for individual pieces of southern pine lumber of data set 8 at −26°C is plotted against green MC. There is a definite trend of increasing change in MOE with increasing green MC. This trend was much less apparent for data set 8 at higher temperatures.

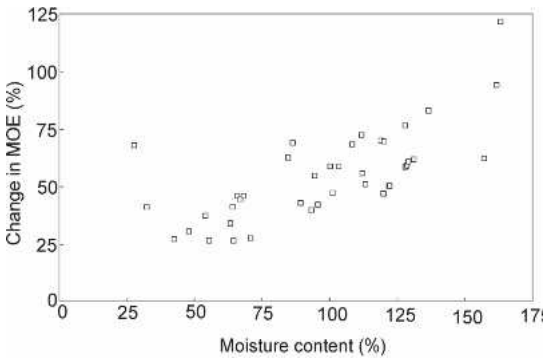

FIGURE 8. Relationship between change in MOE and moisture content for individual pieces of green southern pine at −26°C.

The apparent interaction of the MOE-temperature relationship with MC for green lumber convinced us to limit the applicability of our model when used with green lumber to temperatures above −18°C. Additional discussion of the effect of MC on the MOE-temperature relationship for green lumber is given in our previous paper (Green et al 1999).

Species Dependency of the MOE-Temperature Relationship at 4% MC

Comments received after publication of our study on temperature effects for green lumber and lumber at 12% MC (Green et al 1999) encouraged us to extent our model to a lower MC. However, trends we saw in our initial research (Figs 1, 5) did not indicate a species interaction for the softwood species tested. Further, we knew that as MC decreased to low levels, the magnitude of the change, and thus the possibility of differences between species, would be much reduced. These observations, coupled with limited resources to conduct an additional study, led us to conclude that we could get satisfactory results by testing only one additional species. We also feel that basing our model on a change in MOE with respect to temperature, as opposed to modeling the absolute value of MOE vs temperature, helps to mitigate potential differences due to species.

Effect of Lumber Quality on Change in MOE

Two observations lead us to the conclusion that the immediate effect of temperature on MOE is not very sensitive to lumber quality (grade). In our original studies on the effect of temperature on MOE (Barrett et al 1989), sample sizes were generally larger than those in our later studies. Using data from the original studies, it is possible to examine the change in MOE as a function of percentile level (Table 3). These data show no consistent pattern of change in MOE with temperature as a function of percentile level and thus suggest a minimal effect of lumber quality on percentage of change in MOE.

Also, data set 8 consisted of approximately equal amounts of Select Structural and No. 2 southern pine lumber. When the data were considered as two data sets, the increase in mean MOE at −18°C was 29% for Select Structural and 24% for No. 2 lumber. At 66°C, the decrease in MOE was 11% for Select Structural and 16% for No. 2 lumber. These changes are

TABLE 2. *Equations for change in MOE-temperature models (Fig 6).*

	% Change in MOE = A + B (temperature)			
	A	B	A	B
Moisture content (%)	T ≤ 0°C		T ≥ 0°C	
≥23	7.3476	−0.8259	7.3475	−0.3226
22	7.0872	−0.7689	7.0851	−0.3112
21	6.8298	−0.7116	6.8294	−0.2999
20	6.5692	−0.6546	6.5710	−0.2884
19	6.3118	−0.5973	6.3094	−0.2770
18	6.0512	−0.5403	6.0537	−0.2657
17	5.7930	−0.4831	5.6981	−0.2534
16	5.5332	−0.4260	5.5325	−0.2430
15	5.2757	−0.3688	5.2968	−0.2319
14	5.0151	−0.3117	4.9804	−0.2219
13	4.7577	−0.2545	4.9867	−0.2111
12	4.4971	−0.1974	4.4971	−0.1974
11	4.2006	−0.1845	4.2006	−0.1845
10	3.9041	−0.1715	3.9041	−0.1715
9	3.6107	−0.1584	3.6107	−0.1584
8	3.3142	−0.1454	3.3142	−0.1454
7	3.0177	−0.1325	3.0177	−0.1325
6	2.7211	−0.1195	2.7211	−0.1195
5	2.4246	−0.1065	2.4246	−0.1065
4	2.1281	−0.0936	2.1281	−0.0936

TABLE 3. *Change in MOE relative to value at 23°C at selected percentile levels.*[a]

Data set	Species[a]	Grade	MC (%)	Temperature (°C)	Change in MOE (%) at various percentile levels				
					5th	25th	50th	75th	90th
6	SP	No 2D	green	−4	12.7	10.4	11.7	9.5	9.1
				2	10.7	10.1	8.1	7.5	9.4
				6	5.5	5.2	6.1	3.5	2.5
				32	−7.7	−5.8	−5.1	−4.6	−1.8
2	SP	No 2D	12.4	−23	8.9	14.6	9.3	9.7	7.5
				−4	1.0	10.6	7.3	5.0	4.0
				2	6.4	6.5	6.6	6.7	3.5
				6	2.2	8.0	2.3	1.3	−4.9
				32	−6.7	−0.2	0.3	1.5	−2.9
1	DF	Special	10.2	−23	7.2	11.2	7.7	7.7	6.1
				2	1.9	5.0	2.4	4.7	0.1
				6	2.5	0.9	−1.5	0.5	−2.6
				32	−7.8	−1.5	−2.0	−2.9	0.8

[a] Source: Barrett et al. 1989
[b] SP is southern pine, DF is Douglas-fir

within the experimental variability of Eqs (4a and 4b). Furthermore, inspection of the data summarized in Figs 1, 3, and 5 fails to show a consistent trend between change in MOE and change in temperature across lumber grade. Thus we conclude that the practical benefits of a more robust species-independent model might outweigh small differences due to lumber quality when developing an analytical model that might be used in engineering standards.

CONCLUSIONS

This study evaluated the immediate effect of temperature on the flexural MOE of commercial lumber for temperatures between 66 and −26°C. The results indicate the following:

1. For dry lumber at 12 and 4% MC, a linear relationship may be used to relate the increase in MOE to decrease in temperature. An inflection point in this relationship was not observed near the freezing point of water at either MC levels. This relationship may be used from 66 to at least −26°C.
2. For green lumber, MOE increases with decreasing temperature. A segmented linear relationship may be used to describe this relationship from 66 to −18°C. The MOE of green lumber is more sensitive to temperatures below 0°C than temperatures above this point. Above −18°C, the MOE adjustment does not depend on the actual MC of green wood.
3. Below −18°C the MOE of green lumber continues to increase with decreasing temperature. However, below this temperature the increase in MOE is a function of the actual MC of the green lumber and the temperature to which the lumber is cooled.
4. Within the limits of our experimental design, neither softwood lumber species nor lumber grade was found to have a major effect on change in MOE with change in temperature.
5. Linear interpolation of values between the results at 4% MC and those for green lumber may be used to estimate the temperature effect on change in MOE at intermediate MC levels.

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