ADJUSTING MODULUS OF ELASTICITY OF LUMBER FOR CHANGES IN TEMPERATURE

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ABSTRACT

This study evaluated the immediate effect of temperature on flexural modulus of elasticity (MOE) of green and dry nominal 2- by 4-inch (standard 38- by 89-mm) structural lumber at temperatures ranging from 150° to -15°F (66° to 26°C). For lumber at 12 percent moisture content (MC), a linear relationship was used to relate the increase in MOE to the decrease in temperature. For green lumber, MOE also increased with decreasing temperature. A segmented linear regression was developed to describe the change in MOE for temperatures from 150° to 0°F (66° to - 18°C). The slope of this relationship was steeper below 32°F (0°C) than above this temperature. The actual MC of green lumber was not a factor above 0°F (- 18°C). Below 0°F, 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. The model is believed to be independent of softwood species and lumber grade. Relative to MOE at 100°F (38°C), results of this research support the C_t factors given in the National Design Specifications (1).

Historically, tests of lumber properties have been conducted in a laboratory under constant conditions of temperature and humidity, which allow the effect of temperature to be separated from the generally greater effect of moisture content (MC). Increasingly, however, tests are being conducted in the field under ambient conditions. For example, bending tests of visually graded lumber in the U.S. In-grade testing program have been conducted in the field using portable equipment (18). Wood temperatures at time of test ranged from about 0° to 90°F (- 18° to 32°C). Such test results must be corrected to room temperature to obtain meaningful results.

In the United States, mechanical grading is a two-step process. First, a machine is used to measure a mechanical or physical property and growth characteristics are visually assessed to sort the lumber into proposed grades. Second, the mechanicaI grades are initially qualified by test, and proof-testing is then performed daily to verify one or more of the assigned properties. Two approaches to mechanical grading are used to manufacture the majority of mechanically graded lumber. In the machine-stress-rated (MSR) system, flatwise bending stiffness along the length of the piece is measured on each piece of lumber. In the machine-evaluated (MEL) system, the density profile along the length and across the width is measured by x-ray (19).

For proof tests, the lumber should be at room temperature. However, with the MSR system, lumber can be sorted frozen or while warm from the kiln. In the latter instance, wood temperatures might average at least 120° to 130°F (50° to 55°C). In cold climates, the current practice is to increase the MSR grade thresholds on mechanical grading machines by up to 10 percent during the cold seasons. Correcting machine threshold settings for actual temperature can result in a significant increase in grade yield by giving proper credit to pieces that are not at the lower temperature extreme assumed by the machine operator. Furthermore, when grade thresholds are returned to lower warm-season values, there is an additional cost for intensive testing to establish new grade threshold settings. In warmer climates or warm seasons, grade thresholds are not adjusted for the lower values measured with hot lumber. Again, temperature corrections can improve grade yield in this situation.

As wood is cooled below normal temperatures, its mechanical properties tend to increase. Conversely, when wood is heated, its mechanical properties de-

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† Forest Products Society Member.
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Forest Prod. J. 49(10):82-94.

crease. 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 temperatnre is termed the reversible or immediate effect; that is, the property will return to the original value when the wood temperature is returned to its original value. The reversible effect is the result of a transitory change in the internal energy level of the wood. In addition to the reversible effect, permanent or irreversible loss in properties may occur when wood is heated to elevated temperatures. This permanent effect is one of temperature degradation of the wood substance, which results in weight loss and lowering of properties when wood is tested at room temperature. *The National Design Specification for Wood Construction* (1) indicates that the properties of wood heated up to 150°F (66°C) for brief periods will essentially return to their original levels when the wood is cooled Prolonged exposure to temperatures above 150°F may result in permanent loss in properties.

The objective of this study was to determine the immediate effect of temperature on the modulus of elasticity (MOE) of structural lumber within the temperature range of -15° to 150°F (-26° to 66°C). Mechanical properties of lumber are typically based on the dimensions of the lumber at time of test. Therefore, this report does not directly consider the effect of temperature on member dimensions. A later paper will address permanent losses in properties caused by prolonged exposure of lumber to higher temperatures.

BACKGROUND

The effect of temperature on the properties of small, clear wood specimens has been studied extensively and is throughly reviewed in the 1982 paper by Charles Gerhards (8). Of the clear wood studies completed since the Gerhards review, of particular note is a series of studies on the effect of temperature on the flexural properties of clear spruce within the temperature range of 140° to -220°F (60° to -140°C) (13,14). In the first phase of this study (13), 0.4- by 0.2- by 5.1-inch (10- by 5.0-by 130-mm) specimens were cut from spruce heartwood and then oven-dried. Specimens were exposed in controlled relative humidity solutions to achieve MCs of 0, 4.5, 8.5, 12.7, 19.0, and 28.5 percent. Specimens were then tested in center-point bending, with four to eight replications per condition. In the second phase of the study (14), specimens were first dried, then saturated with water to achieve an MC of 210 percent, and finally air-dried to target MCs of 50, 80, 110, 150, and 210 percent. For green spruce, the percentage of change in MOE, relative to that at 68°F (20°C), was found to increase linearly with decreasing temperature (from 140° to 32°F (60° to 0°C)), regardless of actual MC (Fig. 1). For green spruce with 110 percent MC or less, a different linear relationship was found below 32°F. The inflection in the linear relationship between MOE and temperature is caused by stiffening of the wood cells as free water in the cell lumens begins to freeze below 32°F. However, spruce specimens with 150, 180, and 210 percent MC were found to exhibit a dramatic increase in MOE between 32° and -4°F (0° and -20°C). For this "fully saturated" lumber,' the relationship between MOE and temperature was still linear below -4°F, but the intercept was a function of MC and the slope was found to decrease slightly as MC decreased. By considering the percentage of water in the saturated cell wall and air voids and frozen water in the cell lumen, Mishiro and Asano (13) used the rule of mixtures to predict wood properties. Their results could lead to the conclusion that with wood of very high MCs, there is insufficient air to compensate for ice expansion in the cell lumens and the increased internal pressure leads to a dramatic increase in MOE. The higher the MC, and therefore the leas air in the lumens, the greater the rise in the MOE-temperature relationship. When wood MC was greater than 110 percent, Mishiro and Asano measured increases in wood dimensions in the tangential, but not the radial, direction for temperatures below 32°F (0°C). Wood dimensions increased with an increase in MC. Increases in wood dimensions during freezing of water in the lumen of water-saturated specimens have also been noted (12). Others (e.g., the work of Geissen, as cited in section 11.3 of Bodig and Jayne (4)) have also observed the stiffening of water for wood with high MC levels if the wood is subjected to low temperatures.

Only a few studies have evaluated the effect of ambient temperatures on the flexural properties of commercial lumber. In the 1980s, in-grade testing of lumber in the United States was conducted in the field using portable equipment (18). At time of test, temperatures of speci-

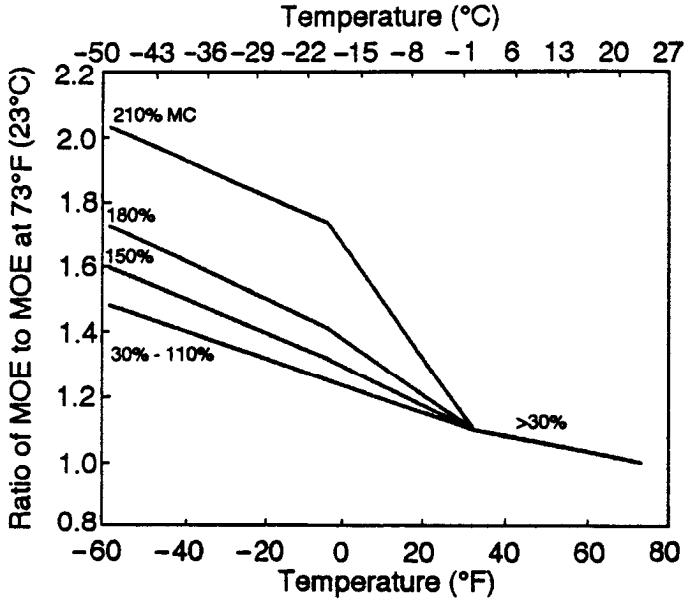

Figure 1. — Effect of temperature on MOE of green spruce (14).

[1] Mishiro and Asano called the wood "saturated" but this term could be confusing if MC were at the fiber saturation point.

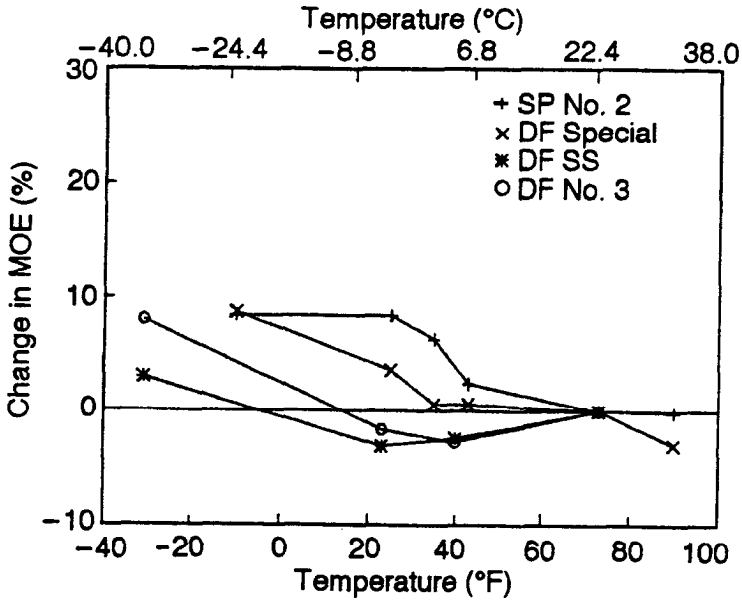

Figure 2. — Effect of temperature on MOE of dry (approx. 12% MC) Douglas-fir (DF) and southern pine (SP) solid-sawn lumber(3).

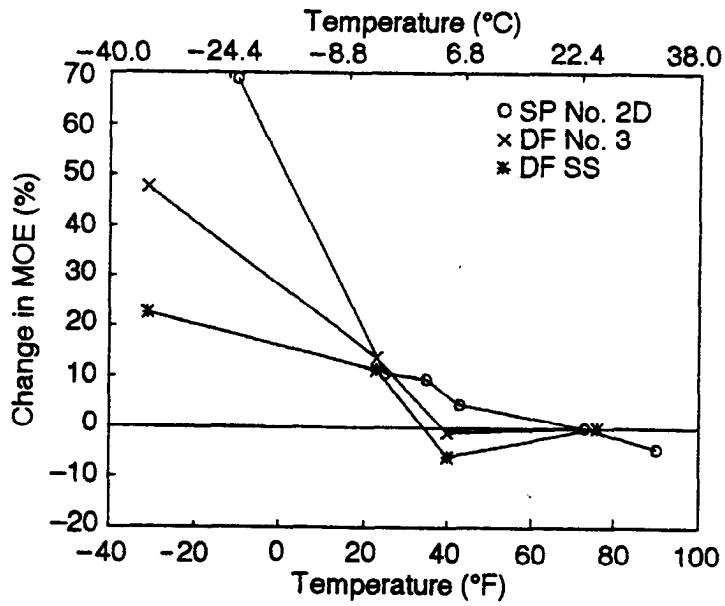

Figure 3. — Effect of temperature on MOE of green Douglas-fir (DF) and southern pine (SP) solid-sawn lumber (3).

TABLE 1. — Effect of temperature on flexural properties of Selected Structural Douglas-fir lumber [a]

MC	Temperature	*n*	50th percentile[b] MOE	50th percentile[b] MOR	Percent difference MOE	Percent difference MOR
(%)	(°F)		(× 10^6 psi)	(× 10^3 psi)	- - - - - - - (%) - - - - - - -	
9.5	73	100	1.84	6.364	0	0
9.4	100	25	1.82	5.719	-1.1	-10.1
9.2	130	25	1.84	5.429	0	-14.7
24	73	25	1.42	4.231	0	0
23	130	25	1.46	3.643	+2.8	-13.9

[a] Source: Fridley et al. (7).
[b] 1 psi = 6.89 kPa.

mens tested in bending ranged from approximately 0° to 90°F (-18° to 32°C) and MC ranged from about 8 percent to green. Independent studies on the effect of temperature on properties of visually graded nominal 2- by 4-inch (standard 38- by 89-mm) and nominal 2- by 6-inch (standard 38- by 140-mm) lumber (hereafter called 2 by 4 and 2 by 6 lumber) at the Forest Products Laboratory and Forintek Canada Corporation were combined to develop adjustment procedures (3). Results indicated that lumber grade and width did not significantly affect MOE with change in temperature. As has been found for clear wood, the MOE of green lumber was found to be more sensitive to change in temperature than was the MOE of lumber at approximately 12 percent MC (Figs. 2 and 3). While the lower end of the temperature range studied (-31°F (-35°C)) was adequate for most purposes, the upper end of the temperature range (90°F (32°C)) is inadequate for kiln-dried lumber that is still warm from processing. Furthermore, as can he seen from Figures 2 and 3, the data sets for Select Structural and No. 3 Douglas-fir initially exhibited a decrease in MOE as temperature decreased below room temperature. Further decreases in temperature resulted in an increase in MOE for both green and dry lumber. The anomalous behavior of these two data sets may have resulted from using (at each temperature) different specimens that had been "matched" by MOE at room temperature rather than exposing all specimens to all temperatures. For lumber at 12 percent MC, the recommended adjustment equation was:

$$\text{\% change in MOE} = 4.8432 - 0.1140T_F$$

$$\text{\% change in MOE} = 1.1958 - 0.2052T_C \qquad [1]$$

where:
T_F = temperature in °F
T_C = temperature in °C

It is assumed that there is no change in MOE with change in temperature from 42° to 90°F (6° to 32°C). The change in MOE was defined as MOE at a given temperature minus MOE at room temperature relative to MOE at room temperature. For green lumber, with a lower cutoff of 45°F (7°C), the recommended equation was:

$$\% \text{ change in MOE} = 27.9140 - 0.6138T_F$$

$$\% \text{ change in MOE} = 8.2724 - 1.1049T_C \quad [2]$$

The lack of data at higher temperatures and practical considerations of the accuracy of in-grade data were used to establish the cutoff temperatures.

Fridley et al. (7) evaluated the effect of temperature on flexural properties of Douglas-fir 2 by 4 lumber as part of a program to evaluate the load-duration behavior of structural lumber. Research on temperature effects was limited to Select Structural lumber and temperatures from 73° to 130°F (23° to 5K). The groups of specimens to be tested at each temperature were "matched" at room temperature by MOE and strength ratio. The results showed little change in MOE when the specimens were heated from 73° to 130°F, and about a 14 percent loss in median MOR **(Table 1).**

DeGeer and Bach (6) developed equations for adjusting the MOE of dry spruce-pine-fir as a function of temperature. Their objective was to evaluate the effect of low temperature on mechanical grading. Their study used two groups of visually graded and two groups of mechanically graded 2 by 4s. The average MC of this lumber ranged from 15 to 17 percent. The study was limited to temperatures of 68°, 5°, and -22°F (20°, -15°, and -30°C). For lumber tested flatwise using a Techmach stress grading machine, the sample size was approximately 120. For edgewise static MOE, the sample size was 10. Again, some data sets exhibited anomalous decreases in static edgewise MOE with decreasing temperature **(Fig. 4).**

Glos and Henrici (9) evaluated the effect of heating on flexural properties of 2.8- by 5.9-inch (70- by 150-mm) spruce lumber. Their study was primarily focused on understanding structural fire design of timber components, and the lumber was therefore heated to 68°, 212°, and 302°F (20°, 100°, and 150°C). The lumber was sorted into units of approximately 26 pieces each; all pieces were equal in quality (density and number of knots) prior to assignment to treatment groups. Final MC at time of test ranged from 13 to 5 percent, depending on treatment group. At an initial MC of 12 percent, static edgewise MOE was reduced about 17 percent as the temperature was increased from 68° to 212°F (20° to 100°C). When the initial MC was 9 percent, the change in MOE was about 8 percent when the wood was heated to 212°F.

The information presented in the preceding discussion indicates a need for additional research on the effect of temperature on lumber MOE that covers a broader range of both cold and hot temperatures. Furthermore, the clear wood test results of Mishiro and Asano (12,14) suggest a need for additional research on properties of green lumber at cold temperatures.

PROCEDURES

PRIMARY DATA

Table 2 summarizes the five 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 by 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 (3). The Douglas-fir lumber (data set 1) was taken from existing supplies at the Forest Products Laboratory (FPL). This 2 by 4 lumber had been graded as No. 1 for strength reductions (e.g., knots) in the middle 24 inches (610 mm) of the span. Because this was not typical No. 1 lumber, the grade of this lumber is called "special." The lumber for data sets 2 and 6 was commercially graded No. 2 Dense (2D) southern pine obtained from a local supplier. The lumber for data set 3 was commercially graded southern pine 2 by 4s in three machine-stress-rated (MSR) grades (1650f-1.5E, 2100f-1.8E, and 2400-2.0E), which was taken from available inventory at FPL. Data sets 4 and 5 consisted of two grades of spruce-pine-fir MSR 2 by 4 lumber: 1650f-1.5E and 2100f-1.8E. The lumber for data set 7 was western hemlock commercially graded at a mill in southeast Alaska. This data set contained an approximately equal mixture of No. 3, No. 2, and Select Structural lumber. The lumber for data set 8 consisted of approximately equal numbers (about 18 pieces each) of Select Structural and No. 2 grade 2 by 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 for data sets 1, 2, and 3 was initially equilibrated at room temperature and 65 percent relative humidity, which corresponds to an anticipated MC of 12 percent (18). For these three data sets, the MOE was determined at one temperature and the specimens were then taken to another chamber for conditioning to an-

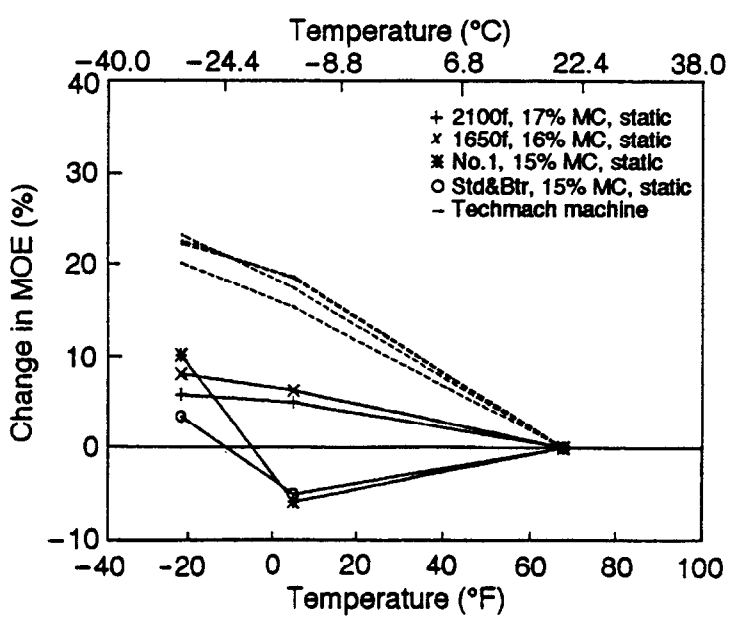

Figure 4. — Effect of temperature on MOE of dry (approx. 19% MC) spruce-pine-fir solid-sawn lumber (6).

other temperature level. Thus, all MOE measurements were taken on the same specimens at all temperatures. In 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 73°F (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 was removed for testing.

The lumber for data sets 1 and 2 was tested on edge in third-point bending according to ASTM D 4761 (2). The span-to-depth ratio of specimens was 17 to 1. In addition, to minimize exposure to room temperature, testing was done at a rate of crosshead motion of 2 inches/minute (51 mm/min.). The MOE of the lumber for data set 3 was determined by transverse vibration (17) over the full length of the specimens. For data set 3, the testing equipment was set up just outside the conditioning room and the lumber was brought out one piece at a time to minimize exposure to room temperature.

Prior to testing, each grade of lumber for data sets 4 and 5 was divided into two groups of equal size 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 stiff-

TABLE 2. — Effect of temperature on lumber MOE for data sets 1 to 8.

Data set	Species	Product	*n*	MC	Temperature[a]	MOE Mean	MOE SD	MOE Minimum	MOE Maximum
				(%)	(°F)	(× 10^6 psi)			
1	Douglas-fir	Special	75	10.2	-10	1.606	0.292	0.96	2.50
					35	1.531	0.299	0.91	2.50
					43	1.487	0.294	0.84	2.57
					73	1.478	0.299	0.85	2.57
					90	1.434	0.272	0.83	2.47
2	Southern pine	No. 2D	50	12.4	-10	1.666	0.320	0.98	2.72
					25	1.613	0.356	0.89	3.02
					35	1.600	0.361	0.85	3.13
					43	1.541	0.302	0.92	2.69
					73	1.505	0.341	0.81	2.82
					90	1.504	0.350	0.80	2.82
3	Southern pine	MSR	30	12.6	-15	2.054	0.555	1.08	3.23
					0	2.035	0.517	1.10	3.00
					36	1.994	0.512	1.07	2.99
					75	1.917	0.484	1.03	2.92
					107	1.897	0.482	1.01	2.74
					150	1.760	0.483	0.86	2.57
4	Spruce-pine-fir	1650f	31	11.0	68	1.571	0.180	1.25	1.99
					150	1.402	0.182	1.10	1.92
5	Spruce-pine-fir	2100f	30	11.5	68	1.868	0.165	1.59	2.32
					150	1.672	0.136	1.43	1.91
6	Southern pine	No. 2D	50	145	-10	2.030	0.342	1.13	2.98
					25	1.331	0.294	0.71	2.40
					35	1.318	0.315	0.71	2.66
					43	1.257	0.288	0.66	2.40
					73	1.201	0.268	0.63	2.07
					90	1.152	0.274	0.57	2.13
7	Western hemlock	No. 3 and btr.	22	53	-15	2.170	0.297	1.49	2.65
					-10	1.928	0.283	1.30	2.43
					0	1.866	0.285	1.24	2.36
					35	1.640	0.279	1.05	2.11
					74	1.541	0.268	1.03	2.01
					107	1.462	0.267	0.94	1.89
					150	1.295	0.269	0.79	1.72
8	Southern pine	SS[b] & No. 2	36	104	-15	1.981	0.345	1.41	2.99
					-10	1.891	0.376	1.33	2.96
					0	1.628	0.416	0.88	2.90
					36	1.348	0.364	0.70	2.47
					74	1.303	0.337	0.64	2.34
					109	1.244	0.348	0.63	2.29
					150	1.138	0.335	0.57	2.14

[a] $T_C = [T_F - 32]/1.8$.
[b] SS = Select Structural.

ness of lumber exposed to high temperatures for extended periods. As with the lumber for data set 3, the MOE values of the lumber for data sets 4 and 5 were determined by transverse vibration using equipment set up just outside the conditioning chamber (150°F (66°C), 75% relative humidity). Following testing, lumber ovendry MC was determined following the procedure of ASTM D 4442 (2).

Following testing in the dry condition, the lumber for data set 6 was placed in a treating cylinder and the cylinder was filled with water at 73°F (23°C). A vacuum of 28 inches (711 mm) of mercury was applied for 1 hour, followed by 125 psi (861 kpa) pressure for 2 hours. 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 10-foot- (3-m-) long pieces Lumber MC was determined prior to the first temperature exposure from sections available when the lumber was cut from the original 14-foot (4.3-m) length to the final length of 10 feet (3 m).

ADDITIONAL DATA

In addition to our "primary" data described in the previous section, we collected additional data sets to help verity the trends in MOE with change in temperature. These data were not used in developing analytical models of the effect of temperature on change in MOE. In our original study (3), matched specimens were also tested at various temperatures to determine modulus of rupture (MOR). The MOE of the lumber to be used for this study was first determined at mom temperature. The specimens were then ranked by MOE at room temperature within a visual grade. Ordered groups of three specimens were then randomly assigned to each of three target temperature groups. Static MOR and MOE values were obtained after conditioning a group of specimens to specified temperature. The MOE of two such matched data sets is summarized as data sets 9 and 10 in **Table 3.** The procedures for these data sets generally followed those described for data sets 1 and 2. Data set 11 consisted of the same specimens described for data set 3 except that MOE was determined by longitudinal stress wave techniques (16). Laminated veneer lumber and laminated strand lumber (15) were also tested at two temperature levels **(Table 3).** This lumber, shown as data sets 12 to 15 in **Table 3,** was part of the same study described for data sets 4 and 5 **(Table 2).**

DEVELOPMENT OF ANALYTICAL MODEL

Previous work on developing analytical models to describe the effect of temperature on flexural properties 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 (3). 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:

$$\% \text{ change in MOE} = 100[(E_T - E_o)/E_o] \quad [3]$$

TABLE 3. — Effect of temperature on lumber MOE for data sets 9 to 15.[a]

Data set	Species	Product[b]	Test[c]	*n*	Temperature	MC	MOE Mean	MOE SD
					(°F)	(%)	------(× 10^6 psi)------	
9	Douglas-fir	Special	Static	50	-10	9.6	1.622	0.266
				50	35	9.3	1.562	0.280
				50	73	9.5	1.563	0.286
10	Southern pine	No. 2D	Static	35	-10	13.3	1.686	0.335
				39	35	13.2	1.597	0.342
				38	73	13.2	1.482	0.339
11	Southern pine	MSR	SW	30	0	12.6	2.093	0.492
				30	36	12.6	2.077	0.493
				30	75	12.6	1.959	0.472
				30	107	12.6	1.929	0.460
				30	150	12.6	1.775	0.438
12	Douglas-fir	LVL	TV	15	68	8.7	2.370	0.120
				15	150	8.7	2.127	0.116
13	Southern pine	LVL	TV	16	68	9.3	2.926	0.167
				16	150	9.3	2.534	0.138
14	Yellow-poplar	LVL	TV	16	68	8.5	2.174	0.126
				16	150	8.5	1.975	0.128
15	Yellow-poplar	LSL	TV	14	68	9.9	1.740	0.144
				14	150	9.0	1.460	0.116

[a] Data not used for analytical model.
[b] LVL = laminated veneer lumber; LSL = laminated strand lumber.
[c] SW = longitudinal stress wave; TV = transverse vibration.

where:

E_T= MOE at temperature T

E_o = MOE at 73°F (23°C)

RESULTS

ESTIMATION OF DRY MOE

Figure 5 summarizes the data for the dry lumber presented in **Table 2.** A "box plot" of the data at a given temperature is shown for each data set. The box plot shows the mean value (x), the middle 50 percent (25th to 75th percentile) of the data (the box), the nominal range of the data (the error bars), and an occasional outlying point (0). 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 **(Fig. 6):**

$$\% \text{ change in MOE} = 7.8553 - 0.1108T_F$$

$$\% \text{ change in MOE} = 4.3104 - 0.1994T_C \quad [4]$$

The regression equation has a coefficient of determination r^2 of 0.93. Also shown in **Figure 6** is a 95 percent confidence interval on MOE values predicted from the regression equation. This model has a slightly flatter slope but a higher intercept than that in Equation **[1].** For dry lumber at about 12 percent MC, Equation **[4]** would predict an approximate 10 percent increase in MOE if lumber were cooled from 73° to -20°F (23° to -29°C) and an approximate 9 percent loss in MOE if lumber were heated to 150°F (66°C). The Equation **[4]** prediction is similar to the results of DeGeer and Bach (6) for static tests at -20°F (-29°C), but less than the result these researchers obtained using the Techmach machine. Equation **[4]** predicts an approximate 7 percent loss in MOE at 130°F (55°C) compared to the lack of change found by Fridley et al. **(7) (Table 1).** At 212°F (100°C), the equation predicts an approximate 16 percent loss in MOE as compared to the 17 percent loss found by Glos and Henrici (9).

Table 3 presents data on the effect of temperature on dry MOE obtained from data sets 9 to 15, which were not used in deriving Equation **[4].** In examining the effect of temperature on bending strength, note that it is impossible to break the same specimen twice. As described earlier for data sets 5 and 6, a common approach is to match specimens by grade and MOE at room temperature and then assign the specimens to target temperature exposure groups. The MOE values of data sets 5 and 6 allow us to compare this approach to that of exposing the same specimens to all temperatures, as was done for data sets 1, 2, and 3 **(Table 2).** In **Figure 7,** mean values from data sets 8 and 9 are superimposed on the regression line and confidence intervals of **Figure 6.** Note that while the overall trend would be about the same as that determined from Equation **[4],** there is considerably more variability in the MOE-temperature trends. This increased variability shows the difficulty of using the matched specimen approach and could help explain why some of the data reported in the literature, including that of our previous work (3), sometimes show an anomalous reduction in MOE with decreasing temperature.

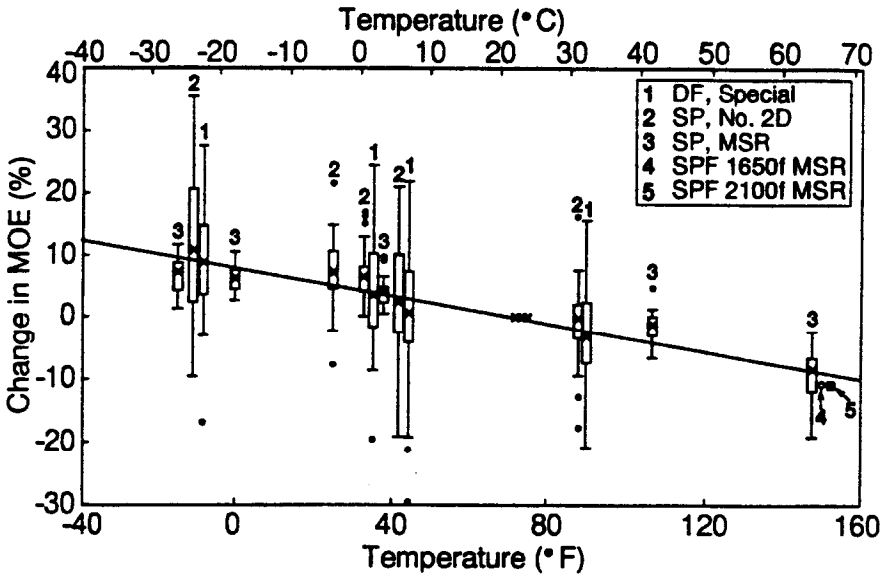

Figure 5. — Effect of temperature on change in MOE for dry spruce-pine-fir (SPF) lumber.

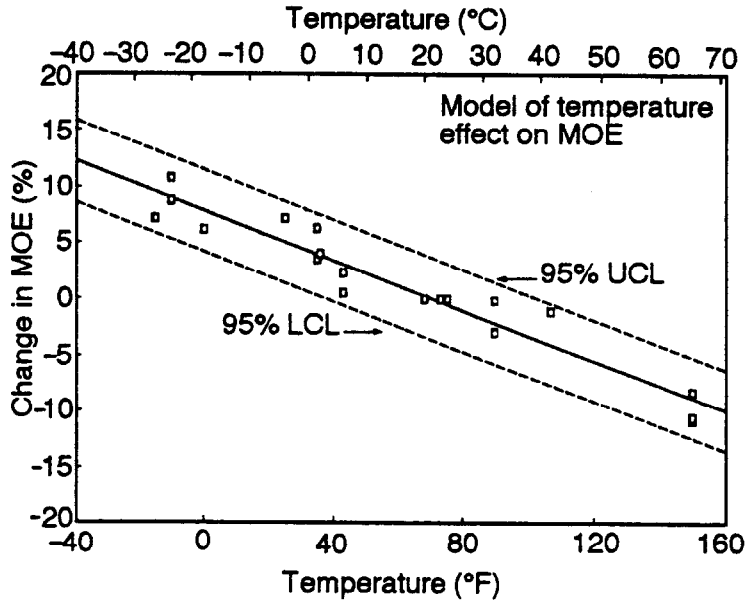

Figure 6. — Modeling of effect of temperature on MOE of dry (12% MC) solid-sawn lumber. LCL and UCL are lower and upper confidence limits, respectively.

Figure 7 also shows the change in MOE for LVL produced from three species (data sets 12 to 14). Again, the change in MOE with change in temperature tended to fall within the 95 percent confidence interval of Equation **[4].** That the southern pine LVL data fall slightly below the lower 95 percent confidence interval is probably more a reflection of the use of small sample sizes and matched specimens than it is of a species difference. The change in MOE from 68° to 150°F (20° to 66°C) averaged -16%. This change was larger than the -8.7 percent predicted by the model and was lower than the 95 percent confidence interval (data point not shown in **Fig. 7).** Thus, we conclude that Equation **[4]** should not be used for yellow-poplar laminated strand lumber.

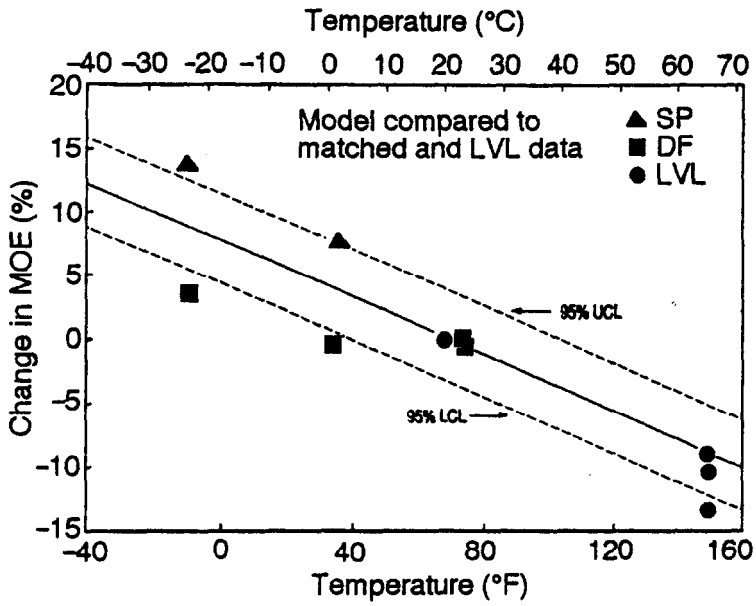

Figure 7. —Comparison of MOE-temperature trends from Figure 6 with results from "matched" specimens of solid-sawn lumber and LVL data.

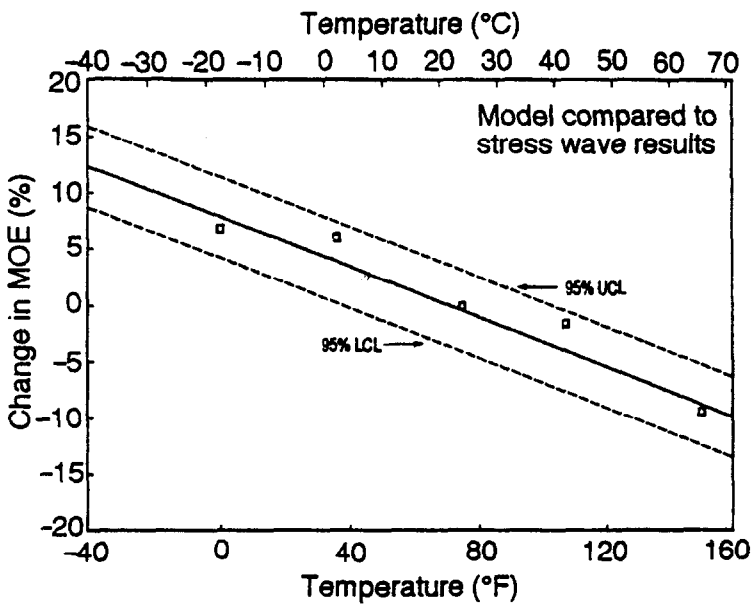

Figure 8. — Comparison of MOE-temperature trends from Figure 6 with MOE of solid-sawn lumber obtained using longitudinal stress wave techniques.

Figure 8 shows the change in MOE for data set 10 **(Table 3),** as determined by longitudinal stress wave techniques (16). Again, the change in MOE falls precisely within the 95 percent confidence interval of Equation **[4]** and is virtually identical to the change in MOE determined by deflection. Thus, the change in MOE with change in temperature described by Equation **[4]** can also be used to adjust longitudinal stress wave MOE values for change in temperature.

ESTIMATION OF GREEN MOE

Figure 9 summarizes the green lumber data presented in **Table 2.** 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 (Eq. **[5]),** except as noted in the following discussion. As will be discussed later, the data in data sets 7 and 8 at -15°F (-26°C) and data set 8 at -10°F (-23°C) were not used in developing Equation **[5].**

If $T \geq 32$°F (0°C),

$$\% \text{ change in MOE} = 13.1215 - 0.1793T_F$$

$$\% \text{ change in MOE} = 7.3837 - 0.3227T_C$$

If $T \leq 32$°F (0°C),

$$\% \text{ change in MOE} = 22.0350 - 0.4578T_F$$

$$\% \text{ change in MOE} = 7.3838 - 0.8241\ T_C \qquad [5]$$

For a segmented regression, an? value is not appropriate. The standard deviation about the regression line is 1.2 percent. Thus, for example, two standard deviations about the mean trend line would be ± 2.4 percent, a very good fit.

ESTIMATION OF MOE AT OTHER MC LEVELS

Because MOE is a function of both MC and temperature, there is need to predict properties at MC values other than the two evaluated in this study. To adjust to other MCs, a linear interpolation is made between the properties predicted by Equations **[4]** and **[5].** This is shown graphically in **Figure 10,** and equations are given in the Appendix. Based on previous research on the effect of MC on properties, the curve for "green" lumber is plotted at 23 percent MC (10,11).

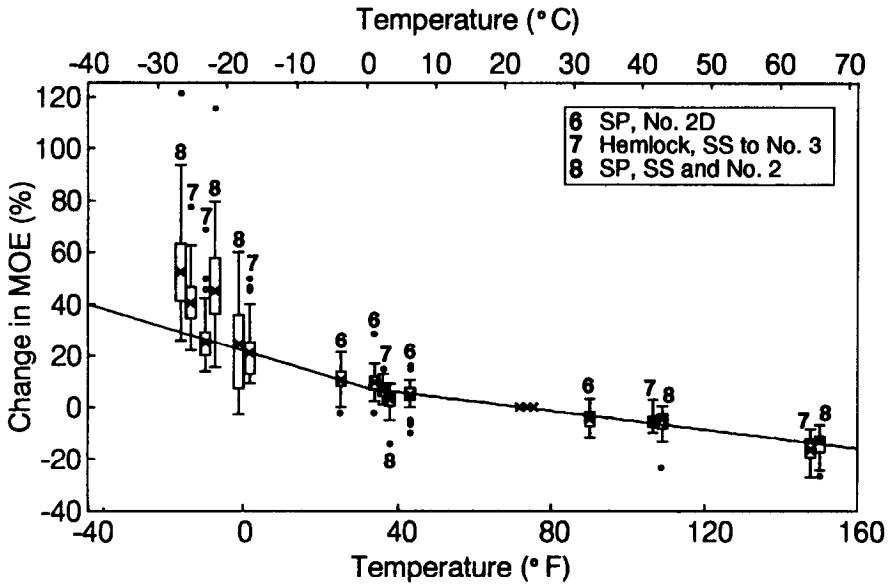

Figure 9. — Effect of temperature on change in MOE for green lumber.

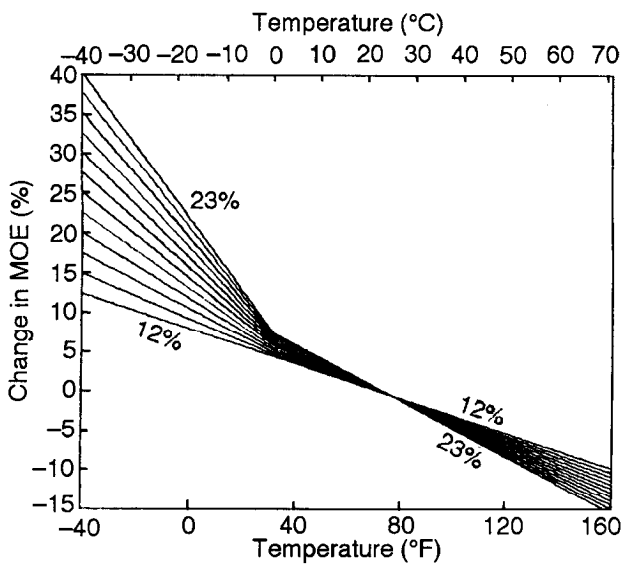

Figure 10. — Predicted relationship between change in MOE and temperature at various MC levels. [Errata: This figure replaces the originally published figure.]

ADDITIONAL CONSIDERATIONS

EFFECT OF MC ON GREEN MOE AT LOW TEMPERATURES

As discussed earlier, Mishiro and Asano (14) found that MC affected the change in MOE for super-saturated clear spruce below 32°F (0°C). It is possible to demonstrate this effect with some of the lumber data from our study. First, observe the error bars for the data presented in **Figure 9** 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 150° to 32°F (66° to 0°C). Below freezing, the variability generally increases with decreasing temperature. Below 0°F (-18°C), the increase in variability does not significantly affect the mean trend between change in MOE and temperature. However, for hemlock at -15°F (-26°C) and for southern pine at -15°F (-26°C) and -10°F (-23°C), the mean trend for data sets 7 and 8 was above the general trend line. The sudden rise in hemlock MOE at -15°F compared to that in southern pine MOE at -10°F was not attributable to species. Rather, this difference was the result of the lower green MC of hemlock (53%) compared to southern pine (104%) **(Table 2).** 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 southern pine. **Figure 11** further illustrates the relationship between green MC and change in MOE at very cold temperatures. Here, the change in MOE for individual pieces of lumber for the southern pine data (data set 8) at -15°F (-26°C) is plotted against the green MC of the piece. 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. As previously discussed, other researchers have measured increased dimensions in water-saturated wood as it freezes. However, our attempts to measure changes in wood dimensions for this lumber were not successful because the lumber had different levels of MC as a result of various amounts of heartwood and sapwood. Our attempts to measure dimensional changes were also hampered by the fact that few pieces had growth ring orientations that were purely radial or tangential.

The interaction of high green MC and cold temperature was also demonstrated when we intentionally increased the MC of the green hemlock in data set 7 **(Table 2).** After this "naturally" green hemlock was tested, the lumber was thawed, placed in a pressure cylinder full of water, and subjected to two pressure-vacuum cycles. The "green" MC of these fully saturated pieces averaged 98.2 percent, with a range from 56 to 152 percent. The lumber was then refrozen to -15°F (-26°C) and the MOE was determined as before. The average increase in MOE of these pieces was 141 percent. In contrast, for the naturally green hemlock with an average MC of 53 percent, the percentage of change from 73° to -15°F (23° to -26°C) was only 40.8 percent.

We speculate that the large increase in MOE at -10°F (-23°C) in our previous southern pine data (data set 6, **Table 2)** may have been caused by "full saturation" of some pieces **(Fig. 2).** Recall that this lumber was first tested at 12 percent MC. "Green" lumber was then obtained

by treating the wood with water in a pressure cylinder. Thus, the MC of these pieces was probably much higher than it would have been if the pieces were "naturally" green. This full saturation probably did not affect the results at 0°F (-18°C) and higher temperatures, but it likely had an effect at -10°F (-23°C). Because some pieces contained more heartwood than others, the pieces with all sapwood might be expected to take up **a** lot of water during treatment while those with all heartwood might take up little water. The increased variability of data set 6, relative to its variability at lower temperatures, probably caused the unexpected increase in MOE relative to that at room temperature.

We also speculate that the apparent difference between Select Structural and No. 3 Douglas-fir at -31°F (-35°C) in **Figure 2** may really be a result of differences in green MC. The average MC of the No. 3 lumber was 80 percent, while that of the Select Structural was 72 percent. The range of MC is not known.

Mishiro and Asano **(14)** found that for green spruce the sudden rise in MOE with decreasing temperatures was related to both MC and the temperature to which the wood was frozen. Chudinov and Stepanov **(5)** investigated the freezing of water in pine and developed an equation to predict the percentage of the water in wood that is frozen. The relative proportion of ice (i) in wood is:

$$i = 1 - [(12 + 18e^{0.0567(t+2)})/MC] \quad [6]$$

where:

t = temperature in °C
MC = percentage of MC
e = basis of the natural logarithms

Equation **[6]** is plotted in **Figure 12.** From **Figure 11** it might be postulated that at -15°F (-26°C), lumber with up to 75 percent MC exhibits "normal" variability. In **Figure 12,** this would correspond to about 78 percent of the water in the wood being frozen. Assuming that 80 percent of the water must be frozen to affect MOE, it is evident that even for MC as low as 50 percent, a sudden rise in MOE would be possible if temperatures were cold enough. However, it is unlikely that wood at 30 to 40 percent MC would ever experience this phenomenon. Chudinov and Stepanov (5) observed that even at -58°F (-50°C), liquid was still present in the cell wall. However, no liquid water was observed in the cell wall at -112°F (-80°C). Below -58°F (-50°C), the amount of liquid water was not significant.

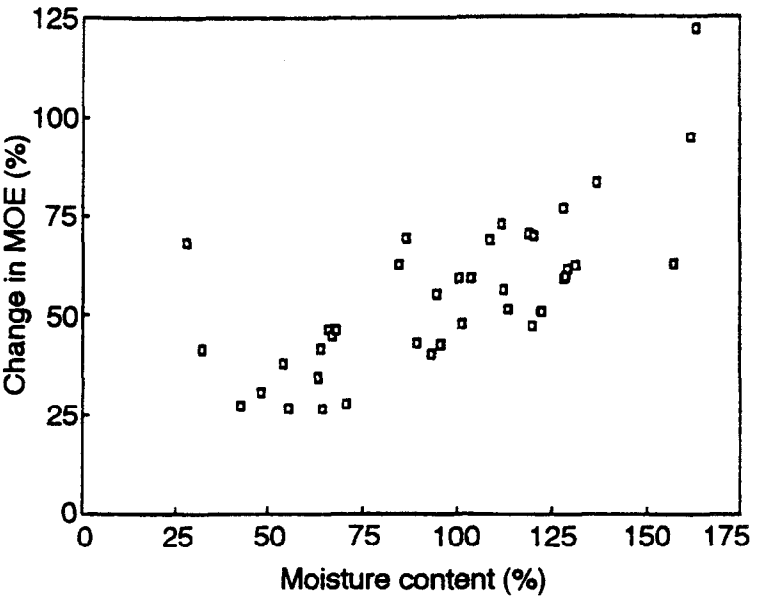

Figure 11. — Relationship between change in MOE and MC for individual pieces of green southern pine at -15°F (-26°C).

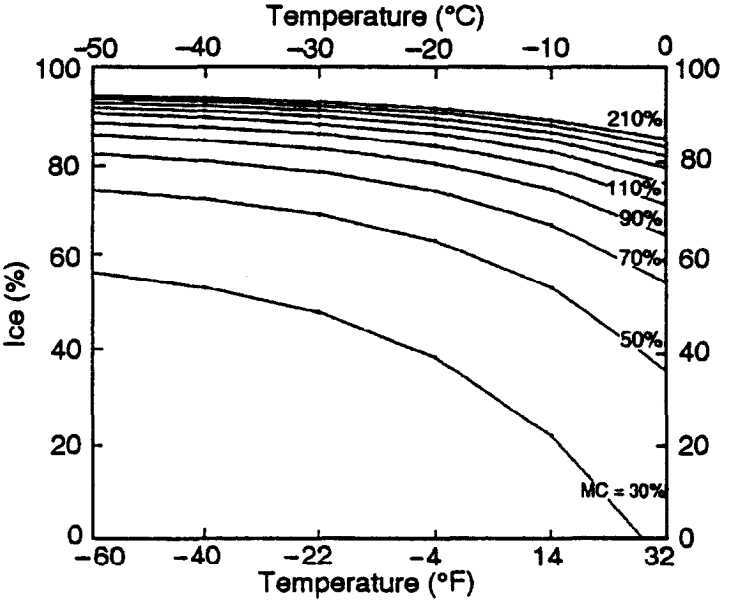

Figure 12. — Predicted percentage of water in frozen southern pine. Adapted from Cudinov and Stepanov (5).

EFFECT OF LUMBER QUALITY ON CHANGE IN MOE

In our earlier studies on the effect of temperature on MOE (3), sample sizes were generally larger than those in our later studies. Using data from the earlier studies, it is possible to examine the change in MOE as a function of percentile level **(Table 4).** These data show no consistent pattern in change in MOE with percentile level and thus suggest a minimal effect of lumber quality on percentage of change in MOE.

As indicated earlier, data set 8 was composed of approximately equal

TABLE 4. — Change in MOE relative to value at 73°F (23°C) at selected percentile levels. [a]

Species	Grade	MC	Temperature	Change in MOE (%) at various percentile levels				
				5th	25th	50th	75th	90th
			(°F)	(%)				
Southern pine	No. 2D	Green	25	12.7	10.4	11.7	9.5	9.1
			35	10.7	10.1	8.1	7.5	9.4
			43	5.5	5.2	6.1	3.5	2.5
			90	-7.7	-5.8	-5.1	-4.6	-1.8
		12.4%	-10	8.9	14.6	9.3	9.7	7.5
			25	1.0	10.6	7.3	5.0	4.0
			35	6.4	6.5	6.6	6.7	3.5
			43	2.2	8.0	2.3	1.3	-4.9
			90	-6.7	-0.2	0.3	1.5	-2.9
Douglas-fir	Special	10.2%	-10	7.2	11.2	7.7	7.7	6.1
			35	1.9	5.0	2.4	4.7	0.1
			43	2.5	0.9	-1.5	0.5	-2.6
			90	-7.8	-1.5	-2.0	-2.9	

[a] Source: Barrett et al. (3).

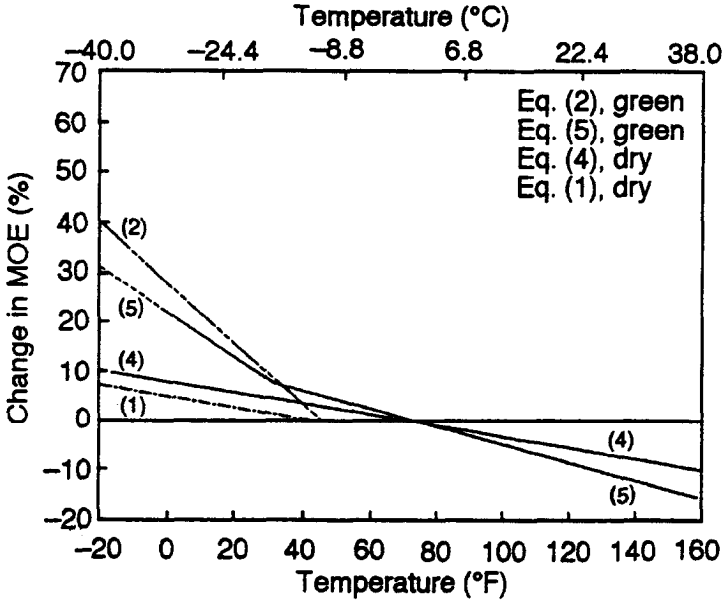

Figure 13. — Comparison of study results with procedures used to adjust in-grade data for effects of temperature at time of test.

amounts of Select Structural and No. 2 southern pine dimension lumber. These data were considered as one data set in the development of Equation **[5].** When the data were considered as two data sets, the increase in mean MOE at 0°F (-18°C) was 29 percent for Select Structural and 24 percent for No. 2 lumber. At 150°F (66°C), the decrease in MOE was 11 percent for Select Structural and 16 percent for No. 2 lumber. These changes are within the experimental variability of Equation **[5].** Furthermore, inspection of the data summarized in **Figures 1** through 3 failed to show a consistent trend between change in MOE and change in temperature across lumber grade.

General trends in the MOE-temperature-MC relationship from our study with lumber are similar to many trends reported in the literature on clear wood. These clear wood studies may be of considerable value in identifying major trends and influences in the property-temperature relationship. Some of these similarities have been discussed previously in this paper or could be noted by observing the trends summarized by Gerhards (8). However, clear wood results may not be directly applicable to lumber. Some clear wood studies have proposed non-linear models, which we found were not needed, and others found higher sensitivity of MOE to temperature than we observed. Thus, care must be exercised when using clear wood research to infer trends for lumber.

COMPARISON WITH STANDARDIZED ADJUSTMENTS

As discussed earlier in the Background section of this paper, MOE data collected in the in-grade testing program were adjusted for temperature using Equations **[1]** and **[2]. Figure 13** compares the results of this study and those of Equations **[1]** and **[2].** As expected with green lumber, the current research predicts less change in adjusting from cold temperature to room conditions than does Equation **[2].** Further, most of the in-grade data were from tests on dry lumber and Equation **[2]** would have produced a conservative adjustment to room temperature. For dry lumber, the results of this study predict a greater change than does Equation **[1].** Although nonconservative, the difference between Equations **[1]** and **[4]** is only approximately 3 percent for lumber at 12 percent MC. This difference may be less at intermediate MC. Consideration should be given to incorporating the results of this study into ASTM D 1990 (2). Once standardized, this would allow evaluation of effects of more precise temperature adjustment procedures, if any, on current allowable design properties.

The NDS lists factors (C_t) that may be used in designing wood structures to account for the immediate effect of heating on MOE. These factors are assumed to

apply to either green or dry wood. From room temperature to 100°F (38°C), the factor is 1.0; from 100° to 125°F (38° to 52°C), the factor is 0.9; and from 125° to 150°F (52° to 66°C), the factor is also 0.9. Relative to 73°F (23°C), the percentage of change in MOE at 100°F (38°C) predicted for dry lumber by Equation **[4]** would be -3.2 percent and Equation **[5]** would predict a -4.8 percent change for green lumber. By implication, the NDS is thus assuming that an approximate 5 percent loss in MOE for green lumber at 100°F (38°C) is not of practical significance. This implied assumption seems reasonable. Relative to 73°F (23°C), Equation **[5]** would predict a 9.3 percent loss in MOE at 125°F (52°C) and a 13.8 percent loss at 150°F (66°C). Relative to 100°F (38°C), our results would thus suggest a C_t factor of 0.96 at 125°F and 0.91 at 150°F. Thus, the NDS recommendations are supported by our results. The NDS does not make recommendations for adjusting properties of cold lumber to room temperature.

Appendix: Equation factors for change in MOE-temperature models (Fig. 10).

MC	% change in MOE = A + B(temp)			
	A	B	A	B
(%)	(T ≤ 32°F)		(T ≥ 32°F)	
23	22.0350	-0.4578	13.1215	-0.1793
22	20.7459	-0.4263	12.6428	-0.1731
21	19.4569	-0.3947	12.1640	-0.1668
20	18.1678	-0.3632	11.6853	-0.1606
19	16.8787	-0.3316	11.2065	-0.1544
18	15.5897	-0.3000	10.7278	4.1482
17	14.3006	-0.2685	10.2490	-0.1419
16	13.0116	-0.2370	9.7703	6.1357
15	11.7225	-0.2054	9.2915	-0.1295
14	10.4334	-0.1739	8.8128	-0.1232
13	9.1444	-.1423	8.3341	-0.1170
12	7.8553	-0.1108	7.8553	-0.1108
	(T ≤ 0°C)		(T ≥ 0°C)	
23	7.3838	-0.8241	7.3837	-0.3227
22	7.1044	-0.7673	7.1044	-0.3115
21	6.8250	-0.7105	6.8250	-0.3003
20	6.5456	-0.6537	6.5456	-0.2891
19	6.2662	-0.5970	6.2662	-0.2779
18	5.9868	-0.5402	5.9868	-0.2667
17	5.7074	-0.4834	5.7074	-0.2555
16	5.4280	-0.4266	5.4280	-0.2443
15	5.1486	-0.3698	5.1486	-0.2330
14	4.8692	-0.3130	4.8692	-0.2218
13	4.5898	-0.2562	4.5898	-0.2106
12	4.3104	-0.1994	4.3104	-0.1994

CONCLUSIONS

This study evaluated the immediate effect of temperature on the modulus of elasticity (MOE) of commercial lumber for temperatures between 150° and -15°F (66° and -26°C). The results indicate the following:

1. For lumber with 12 percent MC, a linear relationship may be used to relate the increase in MOE to the decrease in temperature. An inflection point in this relationship was not observed near the freezing point of water. This relationship may be used from 150° to at least -15°F (66° to -26°C).

2. For green lumber, MOE increases with decreasing temperature. A segmented linear relationship may be used to describe this relationship from 150° to 0°F (66° to -18°C). MOE of green lumber is more sensitive to temperatures below 32°F (0°C) than temperatures above this point. Above 0°F (-18°C), the MOE adjustment does not depend upon the actual MC of green wood.

3. Below 0°F (-18°C), 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. Comparison of our results with those presented in the literature suggest that the model could be used for green lumber with an MC of 30 to 40 percent at -15°F (-26°C) or lower.

4. Neither softwood lumber species nor lumber grade was found to have a major effect on change in MOE with change in temperature. The relationships would also appear applicable to laminated veneer lumber, but not laminated strand lumber.

5. The relationships developed here can be applied to modeling the change in MOE with change in temperature determined in either edgewise or flatwise bending and to MOE of dry lumber determined by longitudinal stress wave techniques.

6. For commercial lumber, our results support that the factors C_t given in the NDS for adjusting MOE for the immediate effect of temperature are conservative relative to MOE at 100°F (38°C).

Linear interpolation of values between the results at 12 percent MC and those for green lumber may be used to estimate the temperature effect on change in MOE at intermediate MC.

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