Effect of Kiln Conditions on the Strength of Douglas Fir and Western Hemlock

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PROGRAM AND PURPOSE

The Forest Research Laboratory of the School of Forestry combines a well-equipped laboratory with a staff of forest and wood scientists in a program designed to improve the forest resource and promote full utilization of forest products. The extensive research done by the Laboratory is supported by the forest industry and by state and federal funds.

The current report results from studies in forest products, where wood scientists and technologists, chemists, and engineers are concerned with properties, processing, utilization, and marketing of wood and of timber by-products.

The PROGRAM of research includes

- identifying and developing chemicals from wood,
- improving pulping of wood and wood residues,
- investigating and improving manufacturing techniques,
- extending life of wood by treating,
- developing better methods of seasoning wood for higher quality and reduced costs,
- cooperating with forest scientists to determine effects of growing conditions on wood properties, and
- evaluating engineering properties of wood and wood-based materials and structures.

The PURPOSE of research on forest products is to expand markets, create new jobs, and bring more dollar returns, thus advancing the interests of forestry and forest industries, by

> developing products from residues and timber now wasted, and

> improving treatment and design of present wood products.

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ABSTRACT

To test the effects of kiln-drying on strength properties of Douglas fir and western hemlock, temperatures to 230 F, conditions for equilibrium moisture contents of 6 percent and 12 percent, and prolonged heating were investigated.

Prolonged heating and choice of conditions for 6 percent or 12 percent equilibrium moisture content had little effect on most strength properties.

Temperature was important: the higher the temperature, the greater the reduction in strength. Toughness was affected most, shear almost as much, modulus of rupture and fiber stress at the proportional limit somewhat less, and modulus of elasticity was affected least.

ACKNOWLEDGMENTS

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EFFECT OF KILN CONDITIONS ON THE STRENGTH OF DOUGLAS FIR AND WESTERN HEMLOCK

Charles J. Kozlik

INTRODUCTION

Work reported here was aimed at providing information as to whether or not kiln-drying affects the strength properties of Douglas fir and western hemlock. A high percentage of Douglas fir and western hemlock is used for structural members, so any reduction of strength resulting from kiln-drying is important. Grading rules consider visible defects that affect strength, but the effect of kiln-drying conditions cannot be evaluated visually.

The effect on solid wood of temperature at various moisture contents has received attention from numerous investigators. Tiemann(9)[1] observed decreases in bending properties of unseasoned wood when the temperature was raised from 127 to 212 F. He also found increased stiffness after cooling the same tested species to 0 and 15 F. Greenhill (4), working with specimens at moisture contents from undried to 5 percent, tested them in a conditioning chamber so that temperature and moisture content of specimens would be maintained during the tests. He found decrease in modulus of elasticity and fiber stress at proportional limit with increasing temperatures from 60 to 180 F.

Sulzberger (8) tested six species in a conditioning chamber at temperatures from -4 to 140 F at moisture contents of 8, 12, and 20 percent, somewhat as done by Greenhill. He reported that modulus of elasticity decreased with increasing temperature, and this effect increased with rising moisture content. Modulus of rupture and fiber stress at proportional limit showed reductions with increasing temperature for all moisture contents. Toughness increased with temperature in some tests but in others remained constant or decreased. Shear properties for hoop pine at 15 percent moisture content showed highly significant linear decreases with increase in temperature from -4 to 104 F.

These investigators considered the effect of temperatures, some of which lay within ranges generally maintained in commercial kiln-drying. In many tests, however, the specimens were heated or cooled

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[1] Numbers in parentheses refer to literature cited.

to desired temperatures at time of testing. Effect of conditions in the kiln on strength is usually considered after wood has been dried to various moisture contents, and strength is not considered during kiln-drying.

MacLean (5) noted that various heat treatments up to 320 F for different periods effected permanent loss of strength in the following order: work to maximum load (greatest loss), modulus of rupture, fiber stress at proportional limit, and modulus of elasticity. Strength was affected more when specimens were heated in saturated steam or were boiled in water than when heated in an oven or hot press.

MacLean (5) in his studies considered loss of strength after the specimens had been heated by various means. The heating conditions were not generally within the range found in dry kilns but resembled those in veneer drying, in treating wood by the Boulton process in the wood-preserving industry, or in subjecting wood in place to high temperatures such as occur on ceilings of boiler rooms.

Salamon (7), compared the effects of conventional drying temperatures (below 212 F) with temperatures above 212 F on the strength of Douglas fir. Drying at high temperature affected strength properties in the following order: modulus of rupture (greatest loss), modulus of elasticity, fiber stress at proportional limit, and maximum crushing strength. Superheated steam drying affected the strength properties as follows: modulus of rupture (greatest loss), maximum crushing strength, fiber stress at proportional limit, and modulus of elasticity. Salamon's investigation included typical commercial schedules which provided excellent comparisons between particular schedules, but the effect of a given temperature and particular conditions for equilibrium moisture content (EMC) cannot be determined from this study.

Alexander and Archer (1) studied effects of five kiln schedules on the strength of western hemlock. They maintained constant temperatures for each schedule and varied the conditions for EMC. They showed that 160 F decreased strength enough to make material unsuitable for construction of aircraft, but they concluded that this reduction would not be so important in other types of construction.

Graham (3) maintained constant temperatures and conditions for EMC on 4- by 8-inch Douglas fir timbers to compare kiln-drying with drying in organic vapors. The strength properties of the timbers kiln-dried at 202 F were affected in the following order: work to maximum load (greatest loss), modulus of rupture, and modulus of elasticity. He concluded that temperatures of 150 F are suitable for Douglas fir.

Graham (3) and Alexander and Archer (1) studied the effects of constant temperatures but did not consider the entire range of temperatures and conditions for EMC now followed in commercial kiln-drying of Douglas fir and western hemlock.

Most mills maintain in their kilns maximum temperatures from 180 to 190 F, with a few mills holding temperature at 150 F. Drying at temperatures exceeding 212 F is becoming more common commercially.

PROCEDURE

After choosing a suitable design for the experiment, material of each species was collected and processed for testing. Square pieces were subjected to various tests to determine the strength properties of the wood.

Design of experiment

The experiment was designed for investigation of the effect of kiln temperatures, conditions for equilibrium moisture content, and prolonged heating on strength properties of Douglas fir and western hemlock. The strength properties investigated included shear parallel to the grain, oriented radially and tangentially; static bending (fiber stress at proportional limit, modulus of rupture, and modulus of elasticity); and toughness, measured radially and tangentially. The temperatures selected were 90 (the basis for comparing effects at other temperatures), 150, 180, 195, 215, and 230 F. At each temperature, conditions for EMC of 6 or 12 percent were applied. The effect of prolonged heating was studied by doubling the time in kiln required at each temperature (except 90 F) with conditions for EMC of 6 percent. Conditions for EMC of 12 percent cannot be obtained at a temperature of 230 F; the method of final analysis was designed to account for this factor. With 6 different temperatures, 2 conditions for EMC (excluding 230 F at conditions for EMC of 12 percent), and the effect of prolonged heating, there were altogether 17 charges. To determine strength properties of unseasoned material, an eighteenth charge was added.

Effect of environment in the kiln on strength properties was studied statistically by employing a factorial design with randomized blocks (replications), based on specific gravity because of its close relation to strength. Specific gravity was determined for each test specimen before drying, and the entire sample for each species was grouped into consecutive specific-gravity classes. Beginning with the lowest specific-gravity class, the first 18 specimens were assigned randomly to 18 test charges. This method of assignment was followed until all specimens to be tested were assigned. Each charge contained 29 pieces of Douglas fir and 35 pieces of western hemlock. The 17 charges for

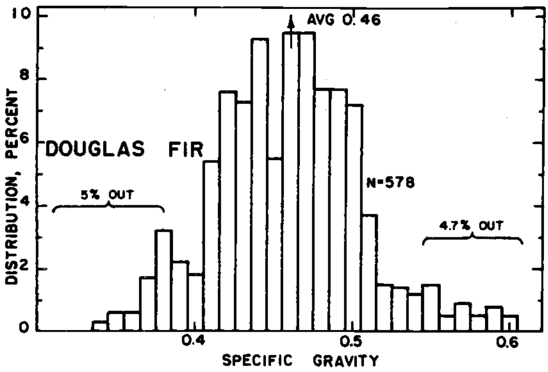
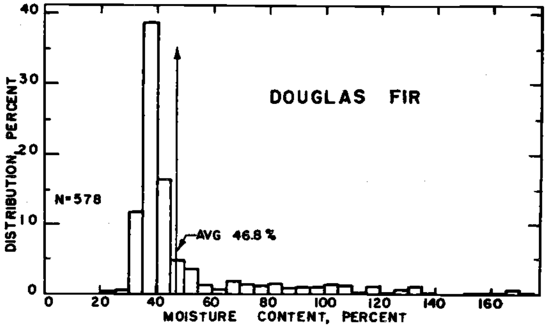


Figure 1. Distribution for specific gravity in 578 pieces of Douglas fir, with highest and lowest values eliminated.

Figure 2. Distribution for moisture content of 578 pieces of Douglas fir.



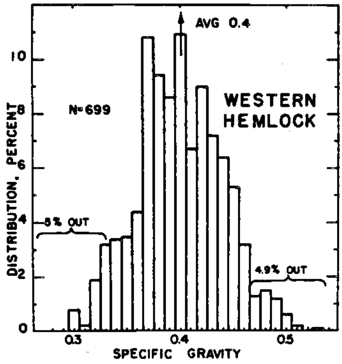


Figure 3. Distribution for specific gravity of 699 pieces of western hemlock, with highest and lowest values eliminated.

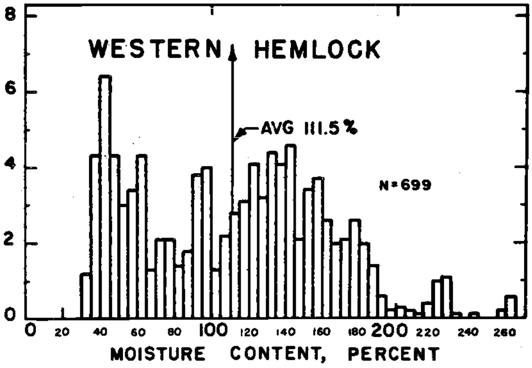


Figure 4. Distribution for moisture content of 699 pieces of western hemlock.

each species were assigned randomly to the various temperatures, conditions for EMC, and effect of prolonged heating, with the remaining charge designated as the unseasoned charge.

Collecting and processing test material

Unseasoned material for testing was collected from 14 lumber mills in the Willamette Valley in Oregon. The lumber usually consisted of 2-inch pieces of clear material of random width and length. Selection was based on the following requirements:

1. Slope of grain no more serious than 1 inch in 20.
2. Freedom from shake, rot, and areas of concentrated pitch.
3. Ring curvature so that maximum distance from a 2-inch chord to its arc would not be more than 1/4 inch.
4. Maximum knot size of 1 inch, providing knots would not interfere in cutting clear specimens for testing.
5. Seven, or more, rings to an inch.

Upon arrival at the Laboratory, the boards to be tested were ripped into 1 7/8-inch strips and blanked in a planer into 1 3/4-inch squares. Each square was cut into 48-inch lengths. Each square was re-examined to ensure that it met the requirements mentioned, had no knots, and had rings oriented in true radial and tangential planes.

To determine moisture content and specific gravity, a wafer about 2 inches long was taken from the end of each 48-inch test square. Specific gravity was based on unseasoned volume and oven-dry weight. Distributions for moisture content and specific gravity for each species are shown in Figures 1,2,3, and 4. The average specific gravity for Douglas fir was 0.46 (Figure 1). Moisture content of Douglas fir averaged 46.8 percent (Figure 2). About 66 percent of the total sample was heartwood.

The average specific gravity for western hemlock was 0.40 (Figure 3). Average moisture content for western hemlock was 111.5 percent (Figure 4). Because it is difficult to distinguish visually between sapwood and heartwood in western hemlock, no estimate of the percentage of heartwood or sapwood in the total sample was made. That the greater percentage of the total sample fell into groups with higher moisture contents does not mean it was sapwood. Since clear specimens were collected, a large number of the samples were "sinker" heartwood coming from the butt logs, which tend to have high moisture contents.

Although the ranges of specific gravity for both species could be considered normal distributions, about 5 percent of the specimens with low and high specific gravity were eliminated (Figures 1 and 3). Part of the sample was eliminated because there were few test specimens of high and low specific gravity, and a very narrow range of specific gravity in each replication was desirable for statistical analysis.

Drying test squares

The charges were dried in a small, experimental dry kiln capable of holding about 100 board feet. Each charge remained in the kiln until moisture content of the squares approached an EMC of 6 or 12 percent. Moisture content was checked by periodically weighing 3 or 4 test squares selected before drying. Drying times for Douglas fir and western hemlock are given in Table 1.

Table 1. Drying Times in Hours.

Treatment	90 F	150 F	180 F	195 F	215 F	230 F
			Douglas fir			
6 percent EMC	4248[1]	268	235	213	176	154
12 percent EMC	1548[2]	240	186	179	168	Not obtainable
Time[3]	4248[4]	536	470	426	352	308
			Western hemlock			
6 percent EMC	4248[1]	258	234	212	168	158
12 percent EMC	432	283	264	237	227	Not obtainable
Time[3]	4248[4]	516	468	424	336	316

[1] Dried in a conditioning chamber at 90 F, 6 percent EMC, with slow movement of air.

[2] Dried in a conditioning chamber at 70 F, 12 percent EMC.

[3] Doubling of time in kiln required for EMC of 6 percent is referred to in text as "prolonged heating."

[4] Time was not doubled at 90 F.

Long drying times for charges dried at 90 F for each species (except the hemlock charge at conditions for EMC of 12 percent) were caused by their being dried in a conditioning chamber where air movement was almost lacking when compared with air velocities in a dry kiln. In addition, the drying times of charges at 90 F were not doubled as were some charges at other temperatures. Prolonging the already extended heating at 90 F probably would not have materially affected the strength of wood for this particular study.

After kiln drying, all test squares were placed in a conditioning chamber (maintained at 90 F at conditions for EMC of 6 percent) for at least 3 months. After equalization in the conditioning chamber, the squares were surfaced to 1 1/2 inches.

Testing

Strength properties tested included static bending, toughness (tested radially and tangentially), and shear parallel to the grain (tested radially and tangentially). Each test square was cut to yield seven specimens: one for testing static bending; two for testing shear parallel to the grain (one in the radial plane and one in the tangential plane); and four for testing toughness (two in the radial and two in the tangential planes). Specimens for testing strength were cut free of any visible seasoning checks. Checks and honeycombing generally occurred on the end of the squares dried at temperatures above 180 F at conditions for EMC of 6 percent.

Tests for strength, except toughness, followed procedures set forth in ASTM Standards, "Tests for Small Clear Timber Specimens" (D 143-52) (2). In static bending, ratio of span to depth was 14:1, or a span length of 21 inches. Load-deflection curves in static bending were plotted by an electronic x-y recorder. The test for toughness followed the procedure outlined in the manual, Forest Products Laboratory's Toughness Testing Machine (10).

A wafer was cut from each specimen for testing static bending upon completion of test to determine moisture content and specific gravity. Specific gravity was based on weight when oven dry and volume at moisture content at time of test.

Analyzing

An electronic computer made all final calculations, including moisture content, specific gravity, fiber stress at proportional limit, modulus of rupture, modulus of elasticity, and maximum shear strength in radial and tangential planes. From these computations, coefficient of variation, means, and sum of squares for each strength property,

Table 2. Factorial Design 1, with 15 Combinations.[1]

90 F			150 F			180 F			195 F			215 F		
6% EMC	12% EMC	Time[2]	6% EMC	12% EMC	Time	6% EMC	12% EMC	Time	6% EMC	12% EMC	Time	6% EMC	12% EMC	Time

[1] For each temperature, number of observations per mean value was 87 for Douglas fir and 105 for western hemlock. For EMC and time, number of observations per mean value was 145 for Douglas fir and 175 for western hemlock.

[2] Doubling of time in kiln required for EMC of 6 percent is referred to in text as "prolonged heating."

Table 3. Factorial Design 2, with 12 Combinations.[1]

90 F		150 F		180 F		195 F		215 F		230 F	
6% EMC	Time[2]	6% EMC	Time	6% EMC	Time	6% EMC	Time	6% EMC	Time	6% EMC	Time

[1] For each temperature, number of observations per mean value was 58 for Douglas fir and 70 for western hemlock. For EMC and time, number of observations per mean value was 174 for Douglas fir and 210 for western hemlock.

[2] Doubling of time in kiln required for EMC of 6 percent is referred to in text as "prolonged heating."

moisture content, and specific gravity were determined for temperatures, conditions for EMC, and prolonged heating.

For study of the two treatments of temperatures and EMC conditions or prolonged heating, two factorial designs were set up for each species. Two designs were necessary because conditions for EMC of 12 percent at 230 F cannot be obtained. The same data were used in the two analyses, but in different combinations, with one analysis including five temperatures and two EMC conditions and prolonged heating, as shown in Table 2, and the second analysis including six temperatures and conditions for 6 percent EMC and prolonged heating, as shown in Table 3.

Duncan's multiple-range test was used to determine significant range at the 5 percent level of probability. The significant ranges, obtained by the multiple-range test in each factorial design, are presented in the following order for each property studied: specific gravity, based on volume at time of test and oven-dry weight; moisture content; shear parallel to the grain, tangentially and radially; static bending (fiber stress at proportional limit, modulus of rupture, and modulus of elasticity); and toughness, tangentially and radially.

RESULTS AND DISCUSSION

Douglas fir

A summary of mean values, increasing from left to right, significant ranges, and coefficients of variation for each property is given for the two treatments, temperature, and EMC conditions or prolonged heating, in each factorial design (Table 4).

Analysis of data. Because the randomized blocks in the factorial designs were based on specific gravity, a nearly identical mean value for specific gravity for each charge was desirable. The analysis showed no significant difference among all mean values. The difference between the highest and lowest mean value was less than 2 percent (Table 4).

The average moisture content at time of test in static bending showed significant differences in factorial design 2 at each temperature, except at 215 and 230 F. The average moisture contents for EMC conditions and prolonged heating in factorial design 1 showed no significant differences, but, in factorial design 2, the treatments were significantly different. A difference in moisture content of 0.08 percentage point, although statistically significant, would not be sufficient to influence properties of wood.

As all material for testing, except specimens tested unseasoned, was equalized in a chamber maintained at conditions for EMC of 6 percent at 90 F, the moisture contents below 6 percent illustrated reduction of the equilibrium moisture content of wood with increase in drying temperatures. All values for strength reported were based on actual moisture content, and values were not adjusted to 6 percent moisture content. The difference between one mean moisture content at a given temperature and the mean at the next higher temperature was small, yet a significant difference existed. This can be attributed to the low coefficient of variation of moisture content at any given temperature.

In design 2, the effects of prolonged heating and drying conditions for EMC of 6 and 12 percent on shear strength tested in the tangential plane showed no significant differences (Table 4). The effect of temperature on shear strength showed a definite grouping by temperatures. The grouping, including temperatures of 90 and 150 F, was significantly different from all other temperatures, and the means were above 1400 psi. The 180-195 F grouping was significantly different, and the mean values were about 1350 psi. The 215 F temperature was significantly different, and the mean value was less than 1300 psi.

Table 4. Mean Values for Effects of Treatments on Strength Properties of Douglas Fir.[1]

Design	Units	Order 1	2	3	4	5	6
				Specific Gravity			
1	Deg F	150	215	90	195	180	
	Means	0.507	0.509	0.510	0.511	0.511	
	CV, %[2]	9	9	9	9	9	
	EMC, %	Time[3]	6	12			
	Means	0.508	0.510	0.510			
	CV, %	9	9	9			
2	Deg F	215	150	230	195	90	180
	Means	0.505	0.507	0.510	0.510	0.511	0.512
	CV, %	9	9	9	9	9	9
	EMC, %	Time	6				
	Means	0.508	0.510				
	CV, %	9	9				
				Moisture Content			
1	Deg F	215	195	180	150	90	
	Means, %	4.91	5.29	5.54	5.86	6.01	
	CV, %	7	5	5	3	4	
	EMC, %	Time	6	12			
	Means, %	5.50	5.52	5.54			
	CV, %	8	9	9			
2	Deg F	230	215	195	180	150	90
	Means, %	4.84	4.89	5.29	5.54	5.87	5.97
	CV, %	6	6	6	5	4	4
	EMC, %	Time	6				
	Means, %	5.36	5.44				
	CV, %	10	9				

Table 4. (Continued)

Design	Units	Order 1	2	3	4	5	6
				Shear in Tangential Plane			
1	Deg F	215	195	180	90	150	
	Means, psi	1262	1329	1367	1445	1481	
	CV, %	22	19	15	15	15	
	EMC, %	Time	6	12			
	Means, psi	1355	1382	1393			
	CV, %	20	19	15			
2	Deg F	215	195	180	230	150	90
	Means, psi	1206	1312	1321	1348	1496	1508
	CV, %	22	20	15	18	16	16
	EMC, %	Time	6				
	Means, psi	1362	1368				
	CV, %	19	19				
				Shear in Radial Plane			
1	Deg F	215	195	90	150	180	
	Means, psi	1618	1668	1769	1805	1857	
	CV, %	31	20	18	17	20	
	EMC, %	Time	6	12			
	Means, psi	1650	1758	1822			
	CV, %	24	20	21			
2	Deg F	215	195	180	150	230	90
	Means, psi	1492	1604	1748	1778	1801	1896
	CV, %	31	21	20	19	24	15
	EMC, %	6	Time				
	Means, psi	1719	1721				
	CV, %	21	24				

Table 4. (Continued)

Design	Units	Order					
		1	2	3	4	5	6
		Fiber Stress at Proportional Limit					
1	Deg F	215	90	195	150	180	
	Means, psi	10629	10789	10818	10987	11036	
	CV, %	15	16	17	15	17	
	EMC, %	6	12	Time			
	Means, psi	10721	10739	11096			
	CV, %	16	16	16			
2	Deg F	230	215	90	150	195	180
	Means, psi	9886	10619	10719	11003	11065	11136
	CV, %	19	15	16	16	17	16
	EMC, %	6	Time				
	Means, psi	10569	10907				
	CV, %	17	17				
		Modulus of Rupture					
1	Deg F	215	195	180	150	90	
	Means, psi	15665	16519	17018	17295	17314	
	CV, %	17	19	16	15	15	
	EMC, %	Time	6	12			
	Means, psi	16696	16794	16796			
	CV, %	18	16	17			
2	Deg F	215	230	195	180	150	90
	Means, psi	15263	15486	16839	17065	17215	17343
	CV, %	17	21	17	16	16	15
	EMC, %	Time	6				
	Means, psi	16451	16619				
	CV, %	18	17				

Table 4. (Continued)

De-sign	Units	Order					
		1	2	3	4	5	6
				Modulus of Elasticity			
1	Deg F	215	90	180	195	150	
	Means, M psi	2144	2171	2212	2217	2220	
	CV, %	15	16	16	15	15	
	EMC, %	6	Time	12			
	Means, M psi	2167	2198	2213			
	CV, %	16	15	15			
2	Deg F	215	90	230	180	195	150
	Means, M psi	2113	2151	2164	2199	2223	2227
	CV, %	15	16	18	16	15	16
	EMC, %	6	Time				
	Means, M psi	2165	2194				
	CV, %	16	16				
				Toughness in Tangential Plane			
1	Deg F	215	195	180	150	90	
	Means, In.-lb	134	150	162	177	178	
	CV, %	35	36	31	28	33	
	EMC, %	6	Time	12			
	Means, In.-lb	158	160	163			
	CV, %	33	36	33			
2	Deg F	215	230	195	180	150	90
	Means, In.-lb	131	133	152	158	176	178
	CV, %	37	37	35	31	30	32
	EMC, %	6	Time				
	Means, In.-lb.	154	155				
	CV, %	34	36				

Table 4. (Continued)

Design	Units	Order					
		1	2	3	4	5	6
				Toughness in Radial Plane			
1	Deg F	215	195	180	150	90	
	Means, In.-lb	89	98	106	117	120	
	CV, %	31	32	29	27	25	
	EMC, %	Time	6	12			
	Means, In.-lb	105	105	108			
	CV, %	32	30	30			
2	Deg F	215	230	195	180	500	90
	Means, In.-lb	86	89	99	105	115	121
	CV, %	32	33	32	28	27	25
	EMC, %	Time	6				
	Means, In.-lb	102	103				
	CV, %	32	31				

[1] Values are arranged in order of increasing magnitude; those underscored by a common line were not different at the 5 percent level of significance according to Duncan's multiple-range test.

[2] Coefficient of variation.

[3] Doubling of time in kiln required for EMC of 6 percent. In text, this treatment is referred to as "prolonged heating."

The reason that the charges dried at 230 F fell within the 180-195 F grouping in factorial design 2 cannot be explained. As previously shown, there was no significant difference in specific gravity, which might have explained the higher value at 230 F. Although significant differences in moisture content existed at each temperature, the actual difference in average moisture contents between 215 and 230 F was slight and probably would not explain the higher value for strength at 230 F.

Comparison of the two factorial designs, disregarding the charges at 230 F, showed a definite decrease in shear strength in the tangential plane as the drying temperature increased. The decrease amounted to about 14 percent for the first analysis and about 20 percent for the second, from the 90-150 F grouping to 215 F.

Maximum values for shear strength in the radial plane show significant difference between prolonged heating and the conditions for EMC of 6 and 12 percent in factorial design 1, although no significant difference existed in factorial design 2 (Table 4). Generally, prolonged heating had an effect on the various strength properties not significantly different from the effect of undoubled time in kiln.

The effect of temperature on shear strength in the radial plane followed the general pattern indicated in shear tested tangentially. Again, the mean at 230 F was higher than at 215 F. If the value at 230 F is disregarded, the material dried at 90, 150, and 180 F comprises a group that is significantly different from material dried at 195 and 215 F.

The effect of temperature on fiber stress at proportional limit showed no significant difference for temperatures from 90 to 215 F, but the effect of 230 F was significantly different (Table 5). A decrease of 7 percent occurred in fiber stress at proportional limit between 215 and 230 F, but only a 4 or 5 percent decrease occurred between the highest mean at 180 F and the value at 215 F.

In both factorial designs, effect of prolonged heating was significantly different from conditions for EMC of 6 and 12 percent. Although moisture contents were slightly lower for all charges subjected to prolonged heating, this difference was not large enough to influence the means.

Effects of EMC conditions and prolonged heating on modulus of rupture showed no significant differences. Temperatures produced two significantly different groups: temperatures from 90 to 195 F had mean values of about 17,000 psi; and temperatures of 215 and 230 F had mean values of about 15,000 psi. There was a decrease of about 11 percent in modulus of rupture with increase in temperature from 90 F to 215 F.

Effects of EMC conditions and prolonged heating on modulus of elasticity showed no significant differences. The analysis showed significant differences between 215 F and the two temperatures 150 and 195 F. The remaining temperatures, including 230 F, did not fall into any specific grouping. Because there was a difference of only 5 percent between the highest and lowest means, the modulus of elasticity probably was not affected materially by increasing temperature.

Effects of EMC conditions and prolonged heating on toughness tested tangentially showed no significant differences. Effect of temperature showed a well-defined decrease in toughness with increasing temperature (Table 5). Three separate groupings by temperatures occurred: 90 and 150 F, with toughness values about 180 in.-lb; 180 and 195 F, with toughness values about 150 in.-lb; and 215 and 230 F, with toughness values about 130 in.-lb. A reduction of about 25 percent in toughness occurred between 90 F and 215 F.

Effects of EMC conditions and prolonged heating on toughness tested radially showed no significant differences. The same definite decrease in toughness, radially, with increasing temperature existed as described for toughness, tangentially. Identical groupings by temperatures occurred; 90 and 150 F, 180 and 195 F, and 215 and 230 F, with a reduction of about 25 percent in toughness, radially, between the 90-150 F grouping and the 215-230 F grouping.

Values for unseasoned Douglas fir. Values for unseasoned coast-type Douglas fir were as follows:

Moisture content, percent		49.0
Specific gravity		0.46
Fiber stress at proportional limit, psi		5200
Modulus of rupture, psi		8200
Modulus of elasticity, M psi		1550
Shear strength, psi	Radial plane	920
	Tangential plane	980
Toughness, In.-lb	Radial plane	105
	Tangential plane	155

Effects of treatments on strength of Douglas fir. Effects of prolonged heating and conditions for EMC of 6 and 12 percent were not so evident as the effect of various temperatures on the strength properties of Douglas fir. Effects of treatments other than temperature on most strength properties tested showed no significant differences. Comparison of mean values for each strength property resulting from the three treatments indicated that conditions for EMC of 12 percent generally gave the higher means. Prolonged heating and conditions for EMC of 6 percent did not show that one had consistently higher values than the other. The differences from conditions for EMC of 12 percent and conditions for EMC of 6 percent and prolonged heating ranged from 1 to 3 percent, except for shear in the radial plane, which had a difference of 10 percent.

These findings suggest that severe drying conditions for EMC of 6 percent, or lower, caused a slight reduction in most strength properties investigated. No test material dried at conditions for EMC of 12 percent, regardless of temperature, exhibited end-checking; but test material dried at conditions for EMC of 6 percent or subjected to prolonged heating at temperatures of 180 F, and above, had end-checking and end-grain honeycombing.

Comparison of findings with other studies. Ordinarily, drying increases the strength of wood, but this increase was less evident as kiln temperatures rose. Values for shear showed a reduction in strength between lower, or conventional, kiln temperatures (90-180 F) and the higher temperatures (195-215 F). In hoop pine, Sulzberger (8) found a linear decrease in shear strength with increase in temperature that was highly significant, but such a decrease was not defined so well in the present study. Values for shear in the radial and tangential planes at 230 F were erratic; values for shear tested radially at 90, 150, and 180 F were not in the same alignment in each factorial design. The irregularity found in shear, tested radially, and the range of coefficients of variation between the temperatures suggests that further testing or improved testing procedure is required.

Effect of temperature on modulus of rupture observed in factorial design 2 of this study was compared with results of studies by Graham (3) and Salamon (7). The following reductions in strength resulted when all values in the three studies were adjusted to 12 percent moisture content:

Graham--7 percent less at 202 F than at 153 F.

Present study--3 percent less at 195 F than at 150 F.

Salamon--16 percent less at 218-222 F than at 170 F.

Present study--8 percent less at 215 F than at 180 F.

Salamon--13 percent less at 225 F than at 170 F.

Present study--8 percent less at 230 F than at 180 F.

Although there were slight differences in comparative temperatures, reductions in strength in the two studies were greater than in the present study. This difference was not explainable, since reduction in modulus of elasticity and fiber stress at proportional limit was similar in all three studies. Although they disagreed on the extent of reduction in modulus of rupture with increasing temperature, the three studies indicated a sharp reduction at 200 F and higher.

The two strength properties least affected were fiber stress at proportional limit and modulus of elasticity. The reduction in modulus of elasticity in factorial design 2 was only 5 percent between the high (150 F) and low values (215 F). Graham (3) found a reduction of 3 percent between 153 F and 202 F . Salamon's results (7) showed reductions of 5 percent between 170 F and 218-222 F and 6 percent between 170 and 225 F. MacLean (5) reported a reduction of 6 percent between the control temperature of 80 F and 215 F with charges heated in an oven for 42 days. The four studies illustrated that modulus of elasticity was least affected, with a maximum decrease of 6 percent up to temperatures as high as 230 F.

For fiber stress at proportional limit, MacLean (5) showed a reduction in strength of 5 percent between charges dried at his control temperature of 80 F and those heated in an oven at 215 F for 42 days. Salamon (7) recorded a reduction of 14 percent between charges dried at 170 F and 218-222 F and a reduction of 11 percent between 170 F and 225 F. The present study showed a reduction of 11 percent between the high value at 180 F and the low value at 230 F. Reduction between the high value at 180 F and the second lowest value at 215 F was only 5 percent. Reduction of fiber stress at proportional limit with increasing temperature was not consistent. The extent of reduction lay between 5 and 10 percent, but this value for strength cannot be determined so accurately as other strength properties (6,8). Although an x-y electronic recorder was used in this study, location of the point of departure from a straight line was difficult to establish with many specimens whenever there was not a sharp break of the load-deflection curve from the straight line.

Toughness was the strength property most affected by temperature. Statistical analysis resulted in definite groupings by temperatures: 90 and 150 F; 180 and 195 F; and 215 and 230 F. There was a reduction of 12-15 percent in toughness, measured radially and tangentially, between each consecutive temperature group, and a reduction of 2[illegible]-26 percent between 90-150 F and the 215-230 F grouping. Little information is available about the effect of temperature on toughness. MacLean (5) did not find a high-percentage reduction in toughness between a control sample dried at 80 F and samples heated in an oven at

320 F or heated in boiling water for varying periods of time. Graham (3) reported a reduction of 25 percent in toughness between temperatures of 153 and 202 F in samples cut from the corners of timbers, but samples cut from the center of timbers increased 6 percent in toughness between 153 and 202 F. Sulzberger (8) stated that the effect of temperature on toughness was variable, and he suggested further investigation. Although other studies do not indicate great reduction in values for toughness with increasing temperature, the number of specimens involved in the present study should make results representative for Douglas fir.

Conclusions for Douglas fir.

1. Values for toughness, measured radially and tangentially, were most affected by increasing temperature. A reduction of 25 percent in toughness occurred in changes from temperatures of 90-150 F to 215-230 F.

2. Disregarding the erratic shear values at 230 F, shear, tested tangentially, was reduced by 15-20 percent between temperatures of 90-150 F and 215 F. Shear in the radial plane was affected to nearly the same extent.

3. Effect of temperature on modulus of rupture showed no significant difference between 90 and 195 F. There was a maximum reduction of 12 percent between 90 and 215 F.

4. Effect of temperature on fiber stress at proportional limit showed no significant difference between 90 and 215 F. There was a reduction of 11 percent between the high value at 180 F and the low value at 230 F.

5. Modulus of elasticity was least effected by temperature. A reduction of 5 percent occurred between the high value at 150 F and the low value at 215 F.

6. Generally, there was not a significant difference between the conditions for EMC of 6 and 12 percent and prolonged heating, but the mean values at conditions for EMC of 12 percent were slightly higher in most tests.

7. The equilibrium moisture content of the wood was lowered as temperatures increased.

8. Toughness was the most variable property studied; shear parallel to the grain was the next most variable. The coefficient of variation increased with temperature for toughness and shear parallel to the grain but did not show this increase for the static bending properties.

Western hemlock

A summary of mean values, increasing from left to right, significant ranges, and coefficients of variation for each property is given for the two treatments, temperature, and EMC conditions or prolonged heating in factorial design (Table 5).

Analysis of data. Because the randomized blocks in the factorial designs were based on specific gravity, a nearly identical mean value for specific gravity for each charge was desirable. The analysis showed no significant difference in mean values, the difference between the highest and lowest mean values was less than 2 percent (Table 5).

Average moisture content at time of test in static bending was significantly different at different levels of temperature. The equilibrium moisture content of western hemlock was higher than that of Douglas fir. Moisture content for Douglas fir was significantly different at each temperature, but that for for hemlock was significantly different in groupings by temperature of 90-150, 180-195, 215, and 230 F (Table 5). Although there was a significant difference between prolonged heating and conditions for EMC of 6 and 12 percent in western hemlock, a maximum difference of 0.21 percent between moisture contents, shown in factorial design 2, could not be considered a factor influencing the strength properties of the wood.

As with Douglas fir, all strength values reported for western hemlock were based on actual moisture content at time of test and were not readjusted to 6 percent moisture content.

Effects of conditions for EMC of 6 and 12 percent and of prolonged heating were not significantly different for shear strength in the tangential plane. Significantly different groupings by temperature were shown in each factorial design (Table 5). Maximum shear strength for different groupings by temperatures was as follows: about 1400 psi for 90-150 F; about 1300 psi for 180-195 F; and about 1200 psi for 215-230 F. In each factorial design, a decrease of 7-8 percent occurred in shear strength between each significantly different temperature grouping, a reduction of 15-16 percent between the high of 90-150 F and the low of 215-230 F.

Effects of the two EMC conditions and prolonged heating, in factorial design 1, on shear strength in the radial plane were not significantly different, but a significant difference was found between prolonged heating and conditions for EMC of 6 percent in factorial design 2. As values from these treatments were not significantly different for other strength properties and a difference in maximum shear of only 53 psi occurred, no explanation can be offered. Effect of temperature in factorial design 1 was not significantly different, but significant differences

Table 5. Mean Values for Effects of Treatments on Strength Properties of Western Hemlock.[1]

De-sign	Units	Order					
		1	2	3	4	5	6
		Specific Gravity					
1	Deg F	195	150	180	90	215	
	Means	0.451	0.452	0.454	0.454	0.456	
	CV, %[2]	10	9	9	9	9	
	EMC, %	Time[3]	6	12			
	Means	0.452	0.454	0.455			
	CV, %	10	9	9			
2	Deg F	150	195	180	215	230	90
	Means	0.452	0.452	0.453	0.453	0.454	0.454
	CV, %	9	10	10	9	9	9
	EMC, %	Time	6				
	Means	0.452	0.454				
	CV, %	10	9				
		Moisture Content					
1	Deg F	215	195	180	90	150	
	Means, %	5.69	6.20	6.24	6.45	6.49	
	CV, %	5	4	4	4	4	
	EMC, %	Time	12	6			
	Means, %	6.10	6.26	6.27			
	CV, %	6	7	5			
2	Deg F	230	215	195	180	150	90
	Means, %	5.33	5.76	6.14	6.17	6.43	6.44
	CV, %	5	5	4	4	3	3
	EMC, %	Time	6				
	Means, %	5.94	6.15				
	CV, %	9	6				

Table 5. (Continued)

Design	Units	Order 1	2	3	4	5	6
		Shear in Tangential Plane					
1	Deg F	215	195	180	150	90	
	Means, psi	1203	1275	1326	1405	1425	
	CV, %	19	18	16	14	15	
	EMC, %	6	Time	12			
	Means, psi	1315	1332	1334			
	CV, %	17	17	17			
2	Deg F	230	215	195	180	150	90
	Means, psi	1202	1211	1285	1299	1382	1440
	CV, %	16	19	18	16	14	15
	EMC, %	Time	6				
	Means, psi	1303	1303				
	CV, %	18	17				
		Shear in Radial Plane					
1	Deg F	180	215	90	195	150	
	Means, psi	1750	1766	1798	1810	1811	
	CV, %	14	18	16	16	16	
	EMC, %	Time	12	6			
	Means, psi	1775	1776	1810			
	CV, %	17	18	16			
2	Deg F	230	180	215	90	150	195
	Means, psi	1655	1724	1766	1801	1818	1853
	CV, %	19	18	18	17	15	14
	EMC, %	Time	6				
	Means, psi	1743	1796				
	CV, %	18	17				

Table 5. (Continued)

Design	Units	Order 1	2	3	4	5	6
			Fiber stress at Proportional Limit				
1	Deg F	195	150	90	180	215	
	Means, psi	9130	9147	9308	9412	9617	
	CV, %	16	15	14	17	17	
	EMC, %	12	6	Time			
	Means, psi	9248	9282	9437			
	CV, %	17	15	15			
2	Deg F	230	195	150	90	180	215
	Means, psi	8959	9226	9230	9252	9379	9713
	CV, %	17	16	14	14	15	17
	EMC, %	6	Time				
	Means, psi	9252	9334				
	CV, %	15	16				
				Modulus of Rupture			
1	Deg F	215	195	90	150	180	
	Means, psi	13925	14212	14478	14623	14757	
	CV, %	17	16	15	14	15	
	EMC, %	12	6	Time			
	Means, psi	14253	14434	14510			
	CV, %	15	16	15			
2	Deg F	230	215	195	150	90	180
	Means, psi	12979	14042	14426	14543	14545	14803
	CV, %	19	18	16	14	15	14
	EMC, %	Time	6				
	Means, psi	14205	14241				
	CV, %	17	16				

Table 5. (Continued)

Design	Units	Order 1	2	3	4	5	6
				Modulus of Elasticity			
1	Deg F	90	195	150	180	215	
	Means, Mpsi	1821	1831	1837	1861	1903	
	CV, %	13	15	15	16	14	
	EMC, %	Time	6	12			
	Means, Mpsi	1832	1849	1870			
	CV, %	15	14	14			
2	Deg F	90	150	195	180	215	230
	Means, Mpsi	1815	1822	1839	1854	1874	1876
	CV, %	13	13	15	15	14	15
	EMC, %	Time	6				
	Means, Mpsi	1840	1854				
	CV, %	15	14				
				Toughness in Tangential Plane			
1	Deg F	215	195	90	180	150	
	Means, In.-lb	143	146	146	157	157	
	CV, %	32	28	26	28	26	
	EMC, %	Time	6	12			
	Means, In.-lb	147	151	151			
	CV, %	29	25	30			
2	Deg F	230	90	215	195	180	150
	Means, In.-lb	125	145	146	148	150	155
	CV, %	36	26	31	27	25	27
	EMC, %	Time	6				
	Means, In.-lb	142	147				
	CV, %	31	27				

Table 5. (Continued)

De-sign	Units	Order					
		1	2	3	4	5	6
				Toughness in Radial Plane			
1	Deg F	215	195	90	150	180	
	Means, In.-lb	94	94	95	100	100	
	CV, %	28	26	26	24	25	
	EMC, %	Time	6	12			
	Means, In.-lb	95	96	98			
	CV, %	27	24	26			
2	Deg F	230	90	215	195	180	150
	Means, In.-lb	84	93	94	96	96	99
	CV, %	32	26	28	25	23	25
	EMC, %	Time	6				
	Means, In.-lb	93	95				
	CV, %	28	25				

[1] Values are arranged in order of increasing magnitude; those underscored by a common line were not different at the 5 percent level of significance according to Duncan's multiple-range test.

[2] Coefficient of variation.

[3] Doubling of time in kiln required for EMC of 6 percent. In text, this treatment is referred to as "prolonged heating."

occurred in factorial design 2, with considerable overlapping of groupings by temperatures. As with Douglas fir, a well-defined decrease of shear strength in the radial plane with increasing temperature did not compare with shear tested tangentially. A reduction of 3 percent in shear, radially, occurred in factorial design 1 between the high value at 150 F and the low value at 180 F. In factorial design 2, a reduction of 11 percent occurred between the high value at 195 F and the low value at 230 F. The irregularity found in shear strength, tested radially, as in Douglas fir, suggests that further testing or improved testing procedure is required.

Effects of EMC conditions and prolonged heating on fiber stress at proportional limit were not significantly different (Table 5). Although groupings by temperatures were found significantly different in each factorial design, the poor alignment of temperatures again emphasizes the chance for error in interpreting the point of departure from a straight line in determining values for this strength property. Mean values for fiber stress were highest at 180 and 215 F, but the mean value at 195 F was one of the lowest observed. In factorial design 1, there was a reduction of 5 percent between the high value at 215 F and the low value at 195 F. In factorial design 2, an 8 percent reduction occurred between the high value at 215 F and the low value at 230 F. As similar reductions were recorded in each factorial design, the influence of temperature on fiber stress at proportional limit was slight and was similar in magnitude to the effect of temperature on modulus of rupture and modulus of elasticity.

Effects of EMC conditions and prolonged heating on modulus of rupture were not significantly different. Significant differences were observed for the effects of temperature. Groupings by temperatures overlapped, but generally the temperatures of 90, 150, and 180 F composed one grouping, with significantly different groupings for 215 and 230 F. The slight decrease of 4 or 5 percent that occurred in modulus of rupture at 195 F dropped to 6 or 12 percent at 230 F.

Alexander and Archer (1) studied the effect of kiln drying on the strength of western hemlock. They maintained five kiln schedules: two with temperatures of 140 F, but with different relative humidities, and three with temperatures of 130, 150, and 160 F. Kiln-dried material was adjusted to 15 percent moisture content and compared for strength with air-dried material. They observed a reduction from 2 to 5 percent with temperatures of 130 and 150 F and a reduction of 9 percent at 160 F. Their study and the present study disagree about reductions in strength at the lower temperatures.

Effects of EMC conditions and prolonged heating on modulus of elasticity were not significantly different. In factorial design 1, significant groupings by temperature resulted; no mean value was significantly different in factorial design 2. In both factorial designs, the mean value at 90 F was the lowest; with fair alignment of temperatures, the modulus of elasticity increased 3 or 4 percent with increasing temperature.

Alexander and Archer (1), adjusting all values to 15 percent moisture content, found an increase in strength of 2-3 percent at 140 F compared with air-drying. Material dried at 130, 150, and 160 F showed a reduction of 2-4 percent compared with air-dried material. Disagreement between the two studies exists, but the extent of differences is not so large as for modulus of rupture.

Effects of EMC conditions and prolonged heating on toughness, tested tangentially, were not significantly different (Table 5). A significant difference occurred in factorial design 1 between groupings by temperature of 150-180 F and 90-195-215 F, but only 230 F was different from other temperatures in the second factorial experiment. Although the percentage of reduction between high and low values, excluding 230 F, was 9 percent in factorial design 1 and 6 percent in factorial design 2, the mean values from 90 to 215 F were similar. The mean value at 230 F was considerably lower than the mean values for temperatures from 90 to 215 F.

Effects of EMC conditions and prolonged heating on toughness, tested radially, were not significantly different. In factorial design 1, the grouping by temperature for 150-180 F was significantly different from the grouping for 195-215 F, with values for charges dried at 90 F falling within each temperature grouping. In factorial design 2, no significant difference existed between charges dried at temperatures between 90 F and 215 F, but these charges differed significantly from the charges dried at 230 F. Although the two factorial designs did not agree statistically for results between 90 and 215 F, reduction from high to low mean values within this range was identical. Temperatures between 90 and 215 F had little effect, but a sharp reduction occurred at 230 F.

<u>Values for unseasoned western hemlock</u>. Values for unseasoned western hemlock in the study are given below:

Moisture content, percent	132.0
Specific gravity	0.39
Fiber stress at proportional limit, psi	4100
Modulus of rupture, psi	7000
Modulus of elasticity, M psi	1370

Shear strength, psi	Radial plane	800
	Tangential plane	810
Toughness, In.-lb	Radial plane	85
	Tangential plane	120

Conclusions for western hemlock.

1. Values for toughness, measured radially and tangentially, are most affected by temperature. A reduction of 19 percent in toughness, tangentially, and 15 percent in toughness, radially, occurred at 230 F. Although significant differences were found in one factorial design at temperatures between 90 and 215 F, the differences between mean values within this range of temperatures are low.

2. The groupings by temperature--90-150 F; 180-195 F; and 215-230 F--had significant effects on shear in the tangential plane. A reduction of about 8 percent in shear, tested tangentially, occurred between each grouping by temperature, with maximum reduction of 15 percent.

Shear in the radial plane was not significantly different between 90 and 215 F in one analysis. Significant differences occurred between 90 and 230 F in the other analysis, but considerable overlapping of groupings by temperature in both analyses suggests that procedure for testing shear radially should be refined.

3. Temperatures of 90, 150, and 180 F did not affect modulus of rupture. Material dried at 215 and 230 F was significantly different from material dried at the lower temperatures; charges dried at 195 F fell into either group. Values for modulus of rupture were reduced by 12 percent at 230 F.

4. Effect of temperatures on fiber stress at proportional limit was significantly different in the analyses, but an overlapping of groupings by temperature occurred. The high mean value occurred at 215 F and the low mean value at 230 F. This finding suggests that fiber stress at proportional limit was slightly affected by temperature.

5. Modulus of elasticity was least affected by temperature. Generally, all mean values were not significantly different, and a reduction of only 4 percent occurred between the low mean value at 90 F and the high mean value at 230 F. A slight increase in modulus of elasticity occurred with increasing temperature.

6. The effects of conditions for EMC of 6 and 12 percent and of prolonged heating were not significant for all strength properties.

7. Increased temperatures lowered the equilibrium moisture content of western hemlock.

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