United States
Department of
Agriculture

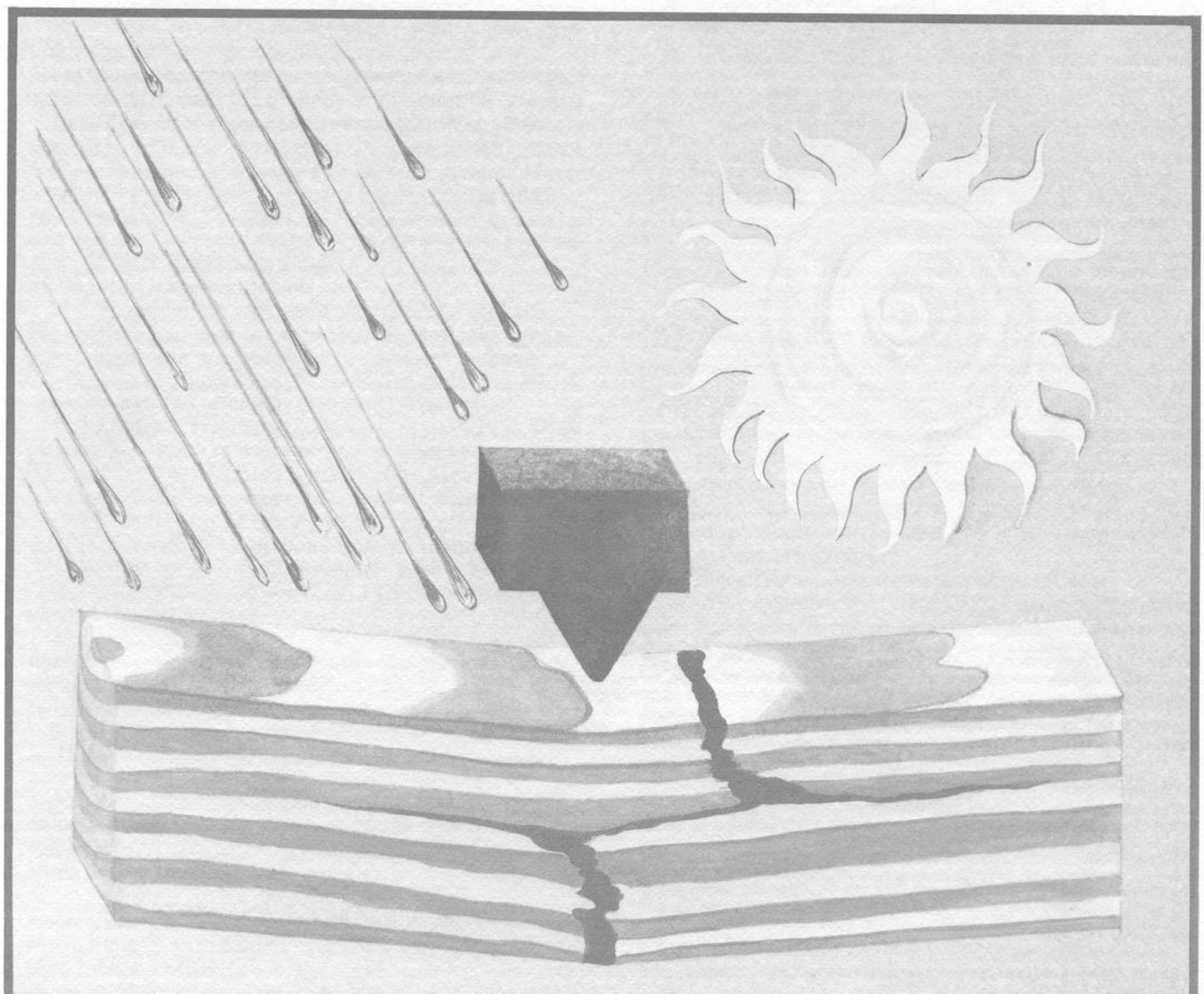
Forest Service

Forest
Products
Laboratory

Research
Paper
FPL 447

The Influence of Moisture Content on the Flexural Properties of Southern Pine Dimension Lumber

T. E. McLain
A. L. DeBonis
D. W. Green
F. J. Wilson
C. L. Link



Abstract

Lumber of three grades (Select Structural, No. 2, and No. 3) and three sizes (2x4, 2x6, and 2x8) was tested to determine the influence of moisture content on the flexural properties of Southern Pine dimension lumber. For each grade-size combination, the sample was divided into four equivalent populations of approximately 100 pieces each, using estimated strength and stiffness in the green condition. Three of the groups were then equilibrated to moisture contents of 10, 15, and 20 percent prior to testing. All samples were tested on edge in third-point bending.

In general, drying increases the flexural properties of Southern Pine dimension lumber. When dried from green to an average moisture content of 15 percent, increases in fifth percentile modulus of rupture, MOR, were in excess of 40 percent for Select Structural lumber. The degree of improvement in lumber strength decreased as lumber quality decreased and width increased. With 2x8, No. 3 material, a decrease in fifth percentile MOR was observed at each successive drying level.

Grade and size had little effect on the moisture content-modulus of elasticity, MOE, relationship. In general, the increases in mean MOE when dried from green to 20, 15, and 10 percent were 5, 22, and 25 percent, respectively.

The largest increase in MOR and MOE generally occurred with drying from 20 to 15 percent. For most grade-size combinations, drying from 15 to 10 percent had little effect on fifth percentile MOR and mean MOE. The potential exists, however, for significant reductions in fifth percentile MOR. This is demonstrated in two of the nine cases where the fifth percentile MOR at 10 percent was about 20 percent less than that at 15 percent.

Investigation of the shape of the cumulative frequency distributions indicated that MOE's were usually normally distributed. With many of the MOR distributions normality was rejected. For No. 2 and No. 3 grade lumber the MOR distributions were symmetric to right skewed (long tail to the right), but for Select Structural they were symmetric to left skewed. The occurrence of left skewed distributions may make the log-normal distribution unsuitable for describing lumber properties as input to reliability based design codes.

Questions as to the applicability of this data to other species and other failure modes will be addressed in subsequent publications. Future reports will also present analytical models and probabilistic procedures for adjusting in-grade data that might also be considered for adoption by engineering code authorities. Until this series of reports is complete, the results of this study should not be incorporated into engineering design codes.

Keywords: Mechanical properties, bending, moisture content, Southern Pine, modulus of rupture, modulus of elasticity, stiffness, moment capacity, distributional form.

October 1984

McLain, T. E.; DeBonis, A. L.; Green, D. W.; Wilson, F. J.; Link, C. L. The influence of moisture content on the flexural properties of Southern Pine dimension lumber. Res. Pap. FPL 447. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 1984.40 p.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, P.O. Box 5130, Madison, WI 53705. Laboratory publications are sent to over 1,000 libraries in the United States and elsewhere.

The forms Douglas Fir and Southern Pine are from the list “Commercial Names for Lumber,” p. 343, In Checklist of United States Trees, Agric. Handb. No. 541, 1979.

The Laboratory is maintained in cooperation with the University of Wisconsin.

Research Highlights

This paper presents the experimental results of a program to evaluate the effect of moisture content on the flexural properties of Southern Pine dimension lumber. This study was initiated because of discrepancies between currently accepted design standards and recent research evidence. The results will be used by FPL to develop procedures for adjusting the data currently being generated in the joint lumber industry-Forest Service in-grade testing program.

Lumber of three grades (Select Structural, No. 2, and No. 3) and three sizes (2 by 4, 2 by 6, and 2 by 8) was sampled from one geographic location. For each grade-size combination the sample was divided into four equivalent populations in terms of estimated strength and stiffness in the green condition. Three of the groups were then equilibrated to moisture contents of 10, 15, and 20 percent prior to testing. All samples were tested on edge in third-point bending.

From comparisons of mean and fifth percentile moduli of rupture (MOR) and mean moduli of elasticity (MOE) we observed that:

1. In general, the absolute increase in mean MOR and mean MOE was dependent upon grade and size. The wider widths and lower grades were generally less affected by drying than were the higher grades and narrower widths. However, moisture content, grade, and size all had a significant effect on the mean values and, for MOR, there was a significant grade by moisture content interaction.
2. Although there was variation by grade and size, the average increase in mean MOR for the nine grade-size groups was approximately 11 percent in drying from green to 20 percent, 35 percent in drying to 15 percent, and 43 percent in drying to 10 percent.
3. For Select Structural lumber, fifth percentile MOR exhibited a significant but erratic increase with drying. When dried to a moisture content of 15 percent, these increases were in excess of 40 percent. Fifth percentile strength of No. 2 and No. 3 grade lumber was less sensitive to moisture content than was the fifth percentile of Select Structural. With 2 x 8, No. 3, a decrease in fifth percentile MOR was observed at each successive drying level.
4. Grade and size had little effect on the average increase.in mean MOE. In general, the increases in mean MOE in drying from green to 20, 15, and 10 percent were 5, 22, and 25 percent, respectively.
5. For most grade-size combinations, drying from 15 to 10 percent had little effect on fifth percentile MOR and mean MOE. The potential exists, however, for significant reductions in fifth percentile MOR. This is demonstrated in two of the nine cases where reductions of approximately 20 percent were observed when drying from 15 to 10 percent.

Analysis of the moment capacity (RS = MOR x section modulus) and stiffness (EI = MOE x moment of inertia) data indicated that:

1. Mean EI was relatively unaffected by drying.
2. Mean and fifth percentile RS were affected by moisture content in the same manner as MOR except that the magnitude of the effect was less for RS than was observed with MOR. The increase in fifth percentile RS was approximately 10 percent less than that for fifth percentile MOR for lumber dried from green to 15 percent.

Based on examination of the experimental cumulative frequency distributions we find that:

1. In general, the effect of moisture content on strength was highest at the upper percentiles. For No. 2 and No. 3 grade lumber, the cumulative frequency distribution for the 10 and 15 percent groups often cross. Below about the 50th percentile, the 10 percent moisture content group was often weaker than the 15 percent group.
2. Drying increased MOE at all levels of the cumulative frequency distribution.
3. The largest increase in MOR and MOE generally occurred with drying from 20 to 15 percent.
4. MOE's were usually normally distributed. With many of the MOR distributions normality was rejected. For No. 2 and No. 3 grade lumber the MOR distributions were symmetric to right skewed, but for Select Structural they were symmetric to left skewed.

Based on these results we conclude that:

1. In general, drying increases the flexural properties of Southern Pine dimension lumber.
2. Improvements in MOR and MOE with drying are significant for Select Structural lumber at virtually all levels of the cumulative frequency distribution. The magnitude of the increase for mean MOE and fifth percentile MOR appears to exceed that assumed in ASTM standard D245-81 for lumber dried to an equilibrium moisture content of 15 percent.
3. The degree of improvement in lumber strength decreases as lumber quality decreases and width increases. For lower grades and wider widths, the 25 percent increase in fifth percentile MOR assumed in D245-81 appears excessive.
4. The effect of moisture content on MOE is relatively independent of lumber size and quality.
5. Drying lumber to an average moisture content less than 15 percent cannot usually be justified on the basis of improvements in flexural strength and stiffness.
6. The occurrence of left skewed distributions may make the log-normal distribution unsuitable for reliability studies of lumber properties.

Questions as to the applicability of this data to other species and other failure modes will be addressed in subsequent publications. Future reports will also present analytical models and probabilistic procedures for adjusting in-grade data that might also be considered for adoption by engineering code authorities. Until this series of reports is complete, the results of this study should not be incorporated into engineering design codes.

Contents

The Influence of Moisture Content on the Flexural Properties of Southern Pine Dimension Lumber

Thomas E. McLain, Associate Professor[1]
A. Louis DeBonis, Assistant Professor’
David W. Green, Research Engineer[2]
Franklyn J. Wilson, Former Graduate Student[1]
Carol L. Link, Mathematical Statistician[2]

Introduction

Extensive in-grade testing programs are currently in progress in the United States to characterize the mechanical properties of existing grades of dimension lumber (Galligan et al. 1980). For reasons of economy, the lumber is tested on portable equipment at sawmill locations. As expected, the moisture content (MC) of this material varies significantly from mill to mill and even within a particular mill. To utilize the data collected from the in-grade testing program with any degree of reliability, it is necessary to evaluate the effect of MC on the strength of dimension lumber. There is also a possibility of species dependency in the mechanical property-moisture relationships among species most commonly used in construction in the United States. Therefore, at a minimum, the relationships for Southern Pine and Douglas Fir need to be established because these are the species being studied in most detail in the in-grade program.

The objective of this study was to investigate the effect of MC on the flexural properties of Southern Pine dimension lumber and to develop analytical models, applicable to in-grade-type data, for adjusting lumber strength data to a common MC level. This paper details the experimental procedure and summarizes some of the experimental results obtained with Southern Pine. Later papers will deal with other aspects of the study.

[1]Department of Forest Products, Virginia Polytechnic Institute and State University, Blacksburg, Va.
[2]Forest Products Laboratory, Madison, Wis.

Background

Traditionally, allowable stresses for dimension lumber in North America have been developed from strength and stiffness data obtained from tests of small, clear specimens in the green MC condition. These data are then adjusted to account for characteristics of full-size lumber such as the presence of knots, slope of grain, and end-use moisture conditions as well as for depth of the member (bending only), duration of load, within species variability, and factor of safety.

The adjustments for seasoning or end-use moisture conditions given in the current American Society for Testing and Materials (ASTM)Standard D 245 (1982) are based on experimental results obtained using structural size members (Green 1980). These adjustments are based on average trends observed for a number of species, but in the standard are assumed to apply without regard to material quality. In earlier versions of ASTM D 245 the magnitude of the moisture adjustment was a function of the quality and size of the member (Green 1980). Indeed, the current adjustment procedure has been questioned, based upon some recent research. Gerhards (1968,. 1970) found that the average dry-green ratio for the modulus of rupture (MOR) of 4 by 8 Southern Pine beams conditioned to an average MC of 12 percent varied linearly from about 1.12 at 25 percent strength ratio to about 1.5 at 100 percent strength ratio. Madsen (1975) also found a material quality dependency between strength and MC from tests conducted on No. 2 and Better Douglas Fir 2 by 6 joists. He concluded that although there was an increase in MOR due to drying at the higher percentile levels, there was no increase at failure stress levels below about 4,000 pounds per square inch (lb/in.^{2}). This level roughly corresponded to the 25th percentile of the strength distribution obtained from his tests. Brynildsen (1977) studied moisture effects on 50- by 150-millimeter (mm) (2.0 by 5.9 in.) European whitewood specimens and concluded that increases in bending strength with drying only occurred for pieces with strengths above approximately 2,850 lb/in.^{2}. Hoffmeyer (1978) conducted similar tests on 45- by 145-mm (1.8 by 5.7 in.) European whitewood joists. This work indicated that MC affects bending strength throughout the entire range of strength, although at lower strength values, this effect was less pronounced.

The differences in the results obtained by Madsen (1975), Brynildsen (1977), and Hoffmeyer (1978) may be attributable to any one or any combination of the following factors: (1) cross-sectional dimensions, (2) species, (3) grading techniques (lumber quality), or (4) conditioning methods. Hoffmeyer (1978) suggested that Madsen's samples were less sensitive to changes in MC because they had not been equilibrated to a constant MC and might have contained a moisture gradient. In a subsequent study, Madsen et al. (1980) concluded that there were no differences between the results obtained by his "dry-out" procedure and those using equilibrated material. However, there was a significant reduction in MOR at the 8 percent MC level for the equilibrated samples as compared to samples containing a moisture gradient. This difference between the equilibrated and the nonequilibrated samples was attributed to degrade in the equilibrated specimens as a result of the length of time they were held at this lower MC. The results of the 8 percent MC were not included by Madsen in subsequent analyses.

In the above research, the effect of MC on modulus of elasticity (MOE) was also investigated. In summary, the following statements may be made:

1. Full-size lumber exhibits a smaller increase in MOE with decreasing MC than do small, clear specimens.
2. There is no consistent evidence that this effect is dependent on material quality.

Materials and Methods

Experimental Design

It was anticipated that the influence of MC on flexural properties might be dependent upon the grade and size of the lumber tested. For this reason, three grades (Select Structural, No. 2, and No. 3) and three sizes (nominal 2 by 4, 2 by 6, and 2 by 8 in.) of Southern Pine lumber were sampled. Each grade-size combination was tested green and after conditioning to one of three target equilibrium MC treatments: 20, 15, and 10 percent. The total number of independent treatment cells was 36.

The experimental design used in this study, with target sample sizes, is shown in figure 1. A target sample size of 100 per cell was felt to be the minimum number required to make statistical inferences about the distribution of strength and stiffness in each cell.

Lumber Selection and Sorting

Lumber was selected from the output of two mills in the fall of 1979. They were located within 20 miles of each other in the tidewater area of southeastern Virginia and northeast North Carolina. The North Carolina mill manufactures lumber but ships it to the Virginia mill for drying and planing. Both mills obtain timber from the same resource base. At the time of sampling the Virginia mill was producing approximately 270,000 board feet of Southern Pine lumber per day and the North Carolina mill slightly less.

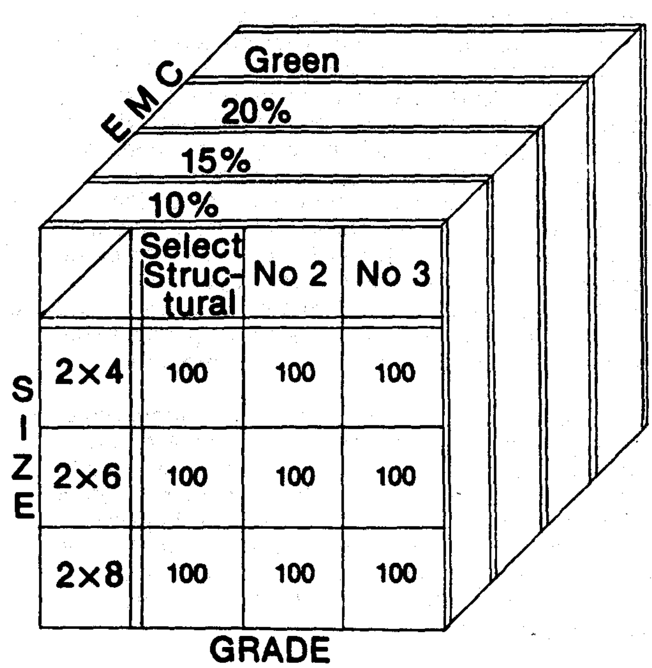


Figure 1.—Experimental design with target sample sizes. (ML84 5317)

For selection of the study boards, rough green lumber in piles of about 200 was brought to a clear area in the mill yard. All 2 by 8's were 12 feet in length; 2 by 6's and 2 by 4's were 10 and 8 feet in length, respectively. Southern Pine Inspection Bureau (SPIB) quality supervisors then examined each board and made a preliminary grade assignment (SPIB 1977). This procedure was continued until the desired number of approximately 400 boards were accumulated in each grade and size group. As the selection process progressed, all accumulated boards were kept tight piled (no stickers were used) and were wetted periodically to prevent any drying of the boards.

When all boards were selected (approximately 4,000), they were planed to the standard 'green dimensions (SPIB 1977) and sprayed with an aqueous solution of a fungicide to prevent fungal growth and retard blue stain on the lumber during the sorting process.

After planing, each piece of lumber was again inspected by SPIB supervisors and grade marked. The supervisor also marked the edge of the board facing him which was used later to indicate the tension edge of the board in the final flexural test. This prevented biasing the location of defects to either the tension or compression edge of the test specimen. In addition, the grader, in consultation with the researchers, determined the grade-controlling and the maximum strength-reducing defect for each board. The grade-controlling defect is the defect responsible for forcing the board to fall in one grade as opposed to the next higher grade. The strength-reducing defect is the principal defect which, in the estimation of the grader and researchers, is responsible for the failure of the board when tested. ASTM D 245 (1982) was used as a guide for this determination. Usually the defect responsible for grade determination was the same as the principal strength-reducing defect. The estimated strength ratio was determined from the maximum strength-reducing defect for each board in accordance with ASTM D 245 (1982) and recorded. The width and depth were measured to the nearest 0.001 inch and recorded for every tenth board. Time considerations prevented measuring every board at this point in the study.

A field flatwise modulus of elasticity (FFMOE) was determined for each piece in the green condition. A concentrated preload and final load were applied at midspan and the difference in midspan deflection between the two loads recorded. The loads were the same for all boards, but the span varied with board size. The 2 by 4's, 2 by 6's, and 2 by 8's were tested over spans of 59.5, 93.5, and 123.5 inches, respectively.

To reduce variation between MC groups due to factors other than the treatment, the green lumber for each of the four MC groups was first sorted by FFMOE. For each grade-size combination all boards were ranked according to FFMOE, from lowest to highest. Boards with equal FFMOE's were further sorted using strength ratios calculated from the maximum strength reducing defect in each piece. Specimens with the lowest four FFMOE values were then randomly assigned to the four moisture levels. Subsequently, the next four pieces were randomly assigned to moisture groups and the process repeated until all samples had been assigned to MC groups. Thus equivalence of the green FFMOE distributions between the four groups was assured. Any correlation between MOR and FFMOE will improve the strength matching between groups over that obtained in a purely random process. This procedure is essentially the same as that proposed by Warren and Madsen (1977).

Kiln Drying and Equilibration to Target Moisture Content Levels

Kiln Drying

After the boards were sorted into treatment groups, the lumber designated for the green group was tight piled and kept wet. To minimize the conditioning time, the lumber samples in the other groups were dried with a very mild kiln schedule. The dry bulb temperature was maintained at approximately 150°F throughout the drying process while the wet bulb temperature was set at 100°F for the first 10 hours of drying and then raised to approximately 130°F for the remaining time. The goal of kiln drying was to reduce the MC of each group to approximately 5 percent above its target MC. Further drying to the target moisture levels was done in equilibration chambers. Care was taken during kiln drying to assure that individual boards did not fall below the target MC levels to avoid excessive degrade and hysteresis effects. Sample boards were placed at various locations in the kiln charge to monitor the actual MC.

After kiln drying, the lumber was wrapped in plastic and transported to Blacksburg, Va., for further equilibration and testing.

Equilibration

The green lumber was stickered and stacked in two chambers equipped with a sprinkler system. The remaining lumber was stickered, stacked, and placed in three separate chambers with conditions controlled to produce equilibrium moisture contents (EMC) of 10, 15, and 20 percent. Because the temperature in the chambers could only be maintained at approximately normal room conditions, the humidity was constantly regulated to maintain proper EMC. The actual MC of the lumber was monitored weekly by using both sample boards and an electrical resistance moisture meter. Conditioning of the 20, 15, and 10 percent groups required about 2, 4, and 6 months, respectively.

Testing Procedures

Before testing, the dry lumber was again regraded by the same SPIB quality supervisors to assess the degrade in each group due to drying. A short-span flatwise modulus of elasticity (SSFMOE) was nondestructively evaluated for each board prior to destructive testing. Procedures were similar to those used to obtain FFMOE except that the test span was only 4 feet.

Except for the rate of loading specification, destructive testing followed the general provisions outlined in ASTM D 198 (1982). This standard recommends a speed of testing which causes the test specimen to fail in about 10 minutes but not less than 6 or greater than 20 minutes. A faster loading rate was utilized to produce times to failure comparable to those observed in the in-grade testing program (Galligan et al. 1980) and to reduce the total time required to test the large number of specimens. The test speed was selected as the rate which would cause the weakest boards in the sample to fail in approximately 1 minute. This rate was found through preliminary tests of low-grade 2 by 4's in the green condition (Wilson 1981). Based on these tests, a crosshead speed of 2 in./min was chosen for all tests. Several studies (DeBonis, Woeste, McLain 1980; Madsen, Barrett 1976; Spencer 1979) have shown that testing speed does not have a significant effect on the flexural strength and stiffness of full-size air-dry lumber for testing speeds within the range of the rate used in this study and that specified in ASTM D 198.

MOR and MOE (uncorrected for shear) were calculated as per ASTM D 198. After test, a l-inch long, full cross-section sample was cut from each board near the area of failure. From this sample the MC and specific gravity (SG) on an ovendry weight/ovendry volume basis were determined according to Method B of ASTM D 2395-69 (1982). Ovendry volumes were used because it was impractical to saturate the large number of dry samples in a reasonable time. Additional details of the experimental procedure are given by Wilson (1981).

Results and Discussion

Verification of Populations

As indicated earlier, field flatwise modulus of elasticity and estimated strength ratio (ESR) were used as nondestructive estimates of MOR and MOE for assigning lumber to different treatment groups. Regression analysis of the properties of the green lumber indicated that the combination of FFMOE and ESR explained about 60 percent of the variation in MOR. This is similar to the results reported by Orosz (1968). Inspection of the mean and coefficient of variation (COV) of FFMOE and ESR for each cell of the experimental design indicates that the segregation scheme produced four approximately equivalent populations (table 1). Analysis of variance of FFMOE and ESR by grade and by size showed no significant differences in mean values (minimum $p = 0.51$). A pairwise comparison of the cumulative distribution function of these properties using the Kolmogorov-Smirnov two sample test statistic (Conover 1980) indicated no significant differences between the treatment groups ($p > 0.75$ for virtually all comparisons).

Average MCs of the different treatment groups were near target values (table 2) with only two averages deviating from the target values by more than 1 percent. The distributions of MCs of the three groups of lumber graphically illustrates the uniqueness of each treatment (fig. 2). In fact, the 95th percentile MC of each group was less than the 5th percentile of the group with the next highest moisture level. The COV's of the 10 and 15 percent treatment groups were generally less than 5 percent, while that of the 20 percent group averaged 6.5 percent. The green material had a large variation because no attempt was made to control this property. However, it is assumed that MC does not influence flexural strength and stiffness of lumber at moisture levels above the fiber saturation point.

Inspection of the average SG presented in table 2 indicates that, for all grade-size combinations, the SG for the group tested green tended to be the lowest of the four values. Given the random manner in which the samples were assigned to the four treatment groups, it is difficult to see why this should have occurred. This specific result is believed to reflect an effect of different drying rates on shrinkage and not a real difference in material properties. Because SG samples were cut from the lumber after conditioning and testing, the 10 and 15 percent groups dried slowly to their respective EMC's before being placed in an oven for determination of ovendry volume. The green and 20 percent samples had little opportunity to shrink prior to being placed in the oven and therefore had to dry rapidly once wafers were cut for the determination of ovendry volumes. It is known that wood dried slowly at high temperatures tends to shrink more than wood dried rapidly (Stevens 1963).

Table 1.--Field flatwise modulus of elasticity and estimated strength ratio of Southern Pine lumber in four moisture content groups[1]

Nominal size	Grade	Moisture content group	Field flatwise modulus Mean	Standard deviation	Coeffi-cient of variation	Mean strength ratios
			—10^6 *lb/in.*^{2}—		— — —*Pct*— — —	
2 x 4	Select Structural	10	1.564	0.335	21.4	90
		15	1.513	0.357	23.6	91
		20	1.519	0.348	22.9	92
		Green	1.480	0.361	24.4	92
	No. 2	10	1.300	0.348	26.8	75
		15	1.285	0.345	26.8	74
		20	1.263	0.364	28.8	75
		Green	1.267	0.340	26.8	74
	No. 3	10	1.251	0.305	24.4	69
		15	1.240	0.341	27.5	65
		20	1.254	0.321	25.6	65
		Green	1.241	0.332	26.7	66
2 x 6	Select Structural	10	1.632	0.340	20.9	91
		15	1.587	0.341	21.5	92
		20	1.574	0.362	23.0	91
		Green	1.590	0.360	22.7	91
	No. 2	10	1.562	0.301	19.2	74
		15	1.425	0.341	23.9	75
		20	1.422	0.364	25.6	74
		Green	1.411	0.370	26.2	74
	No. 3	10	1.351	0.387	28.6	69
		15	1.367	0.370	27.1	71
		20	1.348	0.367	27.3	70
		Green	1.350	0.375	27.8	70
2 x 8	Select Structural	10	1.492	0.331	22.2	90
		15	1.491	0.345	23.1	90
		20	1.473	0.353	24.0	90
		Green	1.458	0.332	22.8	90
	No. 2	10	1.268	0.288	22.7	70
		15	1.300	0.355	27.3	73
		20	1.283	0.305	23.7	70
		Green	1.260	0.298	23.6	72
	No. 3	10	1.282	0.381	29.7	67
		15	1.286	0.347	27.0	69
		20	1.272	0.373	29.4	68
		Green	1.339	0.410	30.6	67

‘Measurements made on green lumber and were the basis for assignment of specimens to the four treatment groups.

Table 2.--Moisture content and specific gravity of Southern Pine lumber in four moisture content groups

Moisture content group	Nominal size	Grade	Sample size	Moisture content Mean	Coeffi-cient of variation	Mean[1]/ ovendry specific gravity
			No.	— — — *Pct* — — —		
Green	2 x 4	Select Structural	130	112.4	22.3	0.522
		No. 2	111	128.9	22.8	.479
		No. 3	84	124.4	29.0	.491
	2 x 6	Select Structural	127	114.8	21.4	.536
		No. 2	121	135.6	18.7	.490
		No. 3	78	131.4	16.9	.490
	2 x 8	Select Structural	141	108.2	24.8	.537
		No. 2	103	120.0	28.0	.497
		No. 3	78	118.1	27.4	.520
20	2 x 4	Select Structural	113	19.2	6.0	.563
		No. 2	112	18.9	5.5	.503
		No. 3	82	18.6	5.5	.496
	2 x 6	Select Structural	112	19.9	5.6	.549
		No. 2	123	19.7	5.0	.501
		No. 3	86	19.8	6.3	.499
	2 x 8	Select Structural	134	20.2	7.8	.542
		No. 2	102	20.2	6.7	.502
		No. 3	79	20.1	8.8	.522
15	2 x 4	Select Structural	111	14.9	3.4	.557
		No. 2	114	14.8	3.5	.516
		No. 3	91	14.9	2.6	.511
	2 x 6	Select Structural	112	14.3	4.2	.556
		No. 2	122	14.3	4.6	.527
		No. 3	87	14.3	4.8	.517
	2 x 8	Select Structural	138	14.4	4.3	.548
		No. 2	97	14.3	3.7	.525
		No. 3	77	14.2	3.6	.520
10	2 x 4	Select Structural	103	10.8	4.3	.546
		No. 2	99	10.7	5.8	.516
		No. 3	96	10.6	2.3	.506
	2 x 6	Select Structural	118	10.5	3.7	.563
		No. 2	111	10.4	4.2	.519
		No. 3	81	10.5	3.6	.519
	2 x 8	Select Structural	131	10.3	4.5	.546
		No. 2	98	10.2	3.9	.505
		No. 3	85	10.2	5.5	.534

‘Based on ovendry weight and volume.

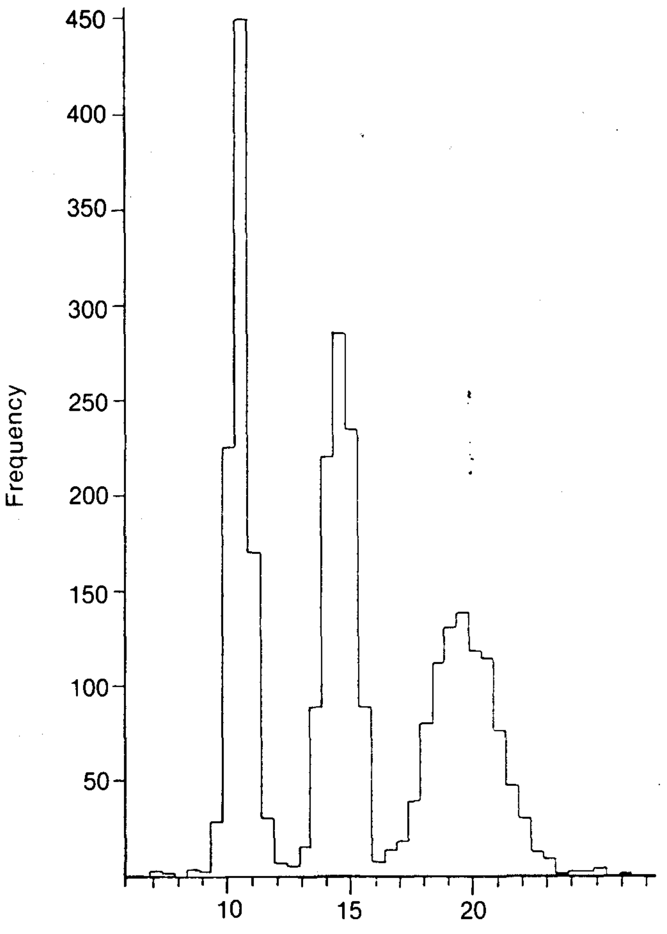


Figure 2.—Distribution of the moisture content of lumber after conditioning to target moisture contents of 10, 15, and 20 percent. (ML84 5318)

This differential drying rate between the wetter and the drier groups could thus explain the apparent differences in SG with treatment groups. Whether or not these differences in SG are real, they are probably not of practical significance because a 2 to 8 percent difference in SG is not likely to affect lumber properties.

Moisture Effects on Mean MOR and MOE

The mean values of MOR and MOE tend to increase with drying as do those of SSFMOE (table 3). Within a moisture content group the No. 2 and No. 3 grade material had a lower mean MOE and MOR than the Select Structural, as expected. However, in a number of cases, there was little difference between the averages of No. 2 and No. 3 lumber. In fact, at three of four moisture levels the mean MOR of 2 by 8, No. 3 lumber exhibited a higher mean than 2 by 8, No. 2 lumber. These trends may be because the criteria for segregating some of the pieces into the No. 3 grade are cosmetic in nature (e.g. wane and warp), and thus the grade-controlling defect may not have a significant influence on average strength.

The variability of MOR and MOE generally increased with decreasing quality of the lumber. This may also reflect the cosmetic nature of some grading criteria. There was no noticeable trend in the variation about the mean MOR with the MC group except that COV was slightly higher for all categories in the 10 percent group. There were no practical differences between the COV's for edgewise MOE of the different MC groups.

Weibull parameter estimates, as well as information concerning the goodness-of-fit of the data to normal and Weibull distributions are given in Appendix A. Cumulative distribution functions, plots of percentiles by MC, and dry-green ratios are presented in Appendix B.

The SSFMOE values generally parallel the MOE values. This indicates that further regression analysis is warranted in order to fully explore the effectiveness of SSFMOE in the mechanical grading of green lumber.

Table 3.--Modulus of rupture and modulus of elasticity of Southern Pine at various moisture contents

				Modulus of elasticity[1]						Modulus of rupture[1]			
				Edgewise			Short-span flatwise						
Nominal size	Grade	Moisture content group	Sample size	Mean	Standard deviation	Coefficient of variation	Mean	Standard deviation	Coefficient of variation	Mean	Standard deviation	Coefficient of variation	Fifth percentile[2]
			No.	— 10^6 *lb/in.*^{2}—		*Pct*	— 10^6 *lb/in.*^{2}—		*Pct*	—*Lb/in.*^{2}—		*Pct*	-*Lb/in.**-
2 x 4	Select Structural	10	103	1.956	0.399	20.4	1.844	0.341	18.5	12,160	3,050	25.1	7,001
		15	111	1.861	0.484	26.0	1.756	0.383	21.8	10,650	2,350	22.1	6,829
		20	113	1.616	0.356	22.0	1.755	0.344	19.6	8,990	1,840	20.5	5,415
		Green	130	1.542	0.372	24.1	1.614	0.355	22.0	7,950	1,870	23.5	4,788
	No. 2	10	99	1.621	0.449	27.7	1.618	0.372	23.0	8,650	3,770	43.6	2,562
		15	114	1.589	0.501	31.5	1.427	0.345	24.2	8,020	2,920	36.4	3,115
		20	112	1.301	0.371	28.5	1.496	0.378	25.3	6,770	2,180	32.2	2,953
		Green	111	1.324	0.369	27.9	1.433	0.371	25.9	6,170	2,170	35.1	2,673
	No. 3	10	96	1.498	0.431	28.8	1.547	0.300	19.4	7,670	3,904	50.9	2,536
		15	91	1.490	0.463	31.1	1.527	0.351	23.0	7,480	3,014	40.3	2,637
		20	82	1.295	0.361	27.9	1.487	0.361	24.3	6,260	2,230	35.6	2,674
		Green	84	1.265	0.366	28.9	1.397	0.370	26.5	5,810	2,202	37.9	2,298
2 x 6	Select Structural	10	118	1.937	0.364	18.8	1.743	0.284	16.3	10,650	2,840	26.7	5,491
		15	112	1.915	0.387	20.2	1.659	0.297	17.9	9,870	2,490	25.2	5,448
		20	112	1.690	0.350	20.7	1.657	0.310	18.7	8,470	1,470	17.4	6,049
		Green	127	1.549	0.347	22.4	1.420	0.275	19.4	7,280	1,704	23.4	3,754
	No. 2	10	111	1.650	0.401	24.3	1.562	0.301	19.3	7,390	3,620	49.0	2,536
		15	122	1.683	0.436	25.9	1.511	0.311	20.6	7,480	3,220	43.1	2,452
		20	123	1.413	0.357	25.3	1.499	0.324	21.6	5,950	1,680	28.2	2,827
		Green	121	1.332	0.372	27.9	1.312	0.306	23.3	5,430	2,297	42.3	1,861
	No. 3	10	81	1.568	0.389	24.8	1.506	0.337	22.4	7,260	3,450	47.5	2,086
		15	87	1.603	0.462	28.8	1.459	0.347	23.8	6,890	3,340	48.4	1,992
		20	86	1.370	0.411	30.0	1.453	0.344	23.7	5,760	2,340	40.6	2,350
		Green	78	1.271	0.377	29.7	1.297	0.336	25.9	4,940	2,179	44.1	1,873
2 x 8	Select Structural	10	131	1.913	0.404	21.1	2.015	0.389	19.3	9,530	3,020	31.7	3,974
		15	138	1.813	0.352	19.4	2.051	0.423	20.6	8,890	2,071	23.3	5,192
		20	134	1.605	0.343	21.4	1.530	0.330	21.6	6,920	1,700	24.5	3,474
		Green	141	1.499	0.319	21.3	1.758	0.381	21.7	6,260	1,660	26.6	3,034
	No. 2	10	98	1.602	0.346	21.6	1.835	0.378	20.6	6,260	3,120	49.9	2,087
		15	97	1.505	0.363	24.1	1.822	0.434	23.8	6,410	2,880	45.0	2,154
		20	102	1.337	0.349	26.1	1.374	0.304	22.1	4,980	2,140	43.0	2,000
		Green	103	1.245	0.312	25.1	1.586	0.376	23.7	4,560	1,780	39.0	1,878
	No. 3	10	85	1.599	0.558	34.9	1.772	0.429	24.2	6,880	3,820	55.5	1,669
		15	77	1.520	0.413	27.2	1.860	0.474	25.5	6,270	2,950	47.0	1,745
		20	79	1.298	0.402	31.0	1.375	0.351	25.5	5,220	2,190	42.0	1,939
		Green	78	1.275	0.358	28.1	1.670	0.423	25.3	4,930	2,080	42.3	2,015

[1]Original data contained three significant digits. Additional digits retained to permit further computations with minimum round-off error.

[2]Nonparametric estimate of the 5th percentile (ASTM D 2915-80, 1982).

Analyses of variance were made using all MOR and MOE data to gain a general overview of the mean effects of the experimental variables (table 4). As expected, MC, size, and grade all had a significant influence on both MOR and MOE. Additionally, the interaction, of MC and grade and the interaction of grade and size was significant for MOR but not for MOE. This indicates a differential influence of MC on the two flexural properties. The interaction of MC and size was not significant for either MOR or MOE. Further analysis of the data will be given in the section on comparison of data sets.

Table 5 presents the ratio of the mean MOR and MOE of dry to that of green lumber. The dry-green ratio of mean bending strength. shows an increase with drying that is consistent with the current adjustments provided by ASTM D 245 (1982). According to this standard, lumber which is dried to a maximum MC of 19 percent (average MC of 15 pct) is allowed a 25 percent increase in allowable design stresses over the green lumber. This increase is not dependent on quality and is assumed to be applicable to all pieces in a grade. All of the dry-green ratios of mean MOR for the 15 percent group are in excess of 1.25. The ASTM D 245 increase for lumber dried to a maximum MC of 15 percent (average MC of 12 pct) is set at 35 percent. This is also generally consistent. with the mean results shown in table 5 as only one value is less than 35 percent in the 10 percent group.

Table 4.—Partial analysls of variance table for modulus of rupture (MOR), and modulus of elasticity (MOE)

Effect	Degees of freedom	H_o: No effect[1] on modulus of rupture F-statistic	p	H_o: No effect[1] on modulus of elasticity F-statistic	p
Grade	2	388.4	< 0.0001	240.8	< 0.0001
Size	2	127.0	< 0.0001	10.3	< 0.0001
Moisture content (MC)	3	211.6	< 0.0001	177.0	< 0.0001
Grade * size	4	4.63	0.0010	1.38	0.2391
MC * grade	6	7.29	<0.0001	1.41	0.2057
MC * size	6	1.03	0.4018	1.52	0.1667
MC * size * grade	12	0.56	0.8723	0.30	0.9899

[1]The null hypothesis is that there is no effect of the factor or interaction on MOR or MOE. p is the probability that if this hypothesis were true one would observe the given differences or larger differences.

The ratios of the. mean values do not show a consistent relationship with material quality (grade) for all sizes and MC groups. A decrease in the ratios of mean MOR and MOE with decreasing grade is most evident for 2 by 4’s and 2 by 8’s. For the 2 by 4’s, the No. 2 and No.. 3 grade material exhibited less of a drying increase than Select Structural. This difference in dry-green, ratios between grades is not always evident with the other sizes.

A comparison of the dry-green ratios at different MC levels for a given grade-size combination indicates that the largest increase in MOR occurs in drying from 20 to 15 percent. Drying from 15 to 10 percent was generally of most benefit for Select Structural material.

The increases in the mean value of edgewise MOE in response to drying was reasonably consistent between all sizes and grades of lumber. In general, a moderate increase was sustained in drying to 20 percent with a much larger increase when the moisture level was reduced to 15 percent. Relatively lower increases in mean MOE were observed between the 15 and 10 percent group, which indicates that the improvement in mean MOE was not linear with decreasing MC. The dry-green ratios for mean MOE also support the ASTM D 245 (1982) adjustments for seasoning (1.14 for drying to an average MC of 15 pct and 1.20 for drying to 12 pct).

Moisture Effects on Fifth Percentile MOR

Current deterministic design procedures for lumber are keyed to an estimate of the lower fifth percentile of the lumber strength distribution. As early as 1912, it was recognized that in full-size lumber with defects there could be a reduction in strength with drying for low-quality pieces (Cline, Heim 1912). Wilson (1932) indicated that the maximum and average strength values of full-size lumber were improved with drying, but the minimum values were not appreciably affected. Green (1980) has outlined the history of MC adjustments for lumber and showed that the differential treatment of minimum and average strength values with respect to moisture effects may have been lost through many revisions of the ASTM standard.

Table 5.--Ratio of dry to green properties for mean edgewise modulus of rupture and modulus of elasticity

Nominal size	Grade	Dry/green fifth percentile ratios: 10 percent moisture content group	15 percent moisture content group	20 percent moisture content group
	MEAN MODULUS OF RUPTURE			
2 x 4	Select Structural	1.53	1.34	1.13
	No. 2	1.40	1.30	1.10
	No. 3	1.32	1.29	1.08
2 x 6	Select Structural	1.46	1.36	1.16
	No. 2	1.36	1.38	1.10
	No. 3	1.47	1.39	1.17
2 x 8	Select Structural	1.52	1.42	1.11
	No. 2	1.37	1.41	1.09
	No. 3	1.40	1.27	1.06
	MEAN MODULUS OF ELASTICITY			
2 x 4	Select Structural	1.27	1.21	1.05
	No. 2	1.22	1.20	0.98
	No. 3	1.18	1.18	1.02
2 x 6	Select Structural	1.25	1.24	1.09
	No. 2	1.24	1.26	1.06
	No. 3	1.23	1.26	1.08
2 x 8	Select Structural	1.28	1.21	1.07
	No. 2	1.29	1.21	1.07
	No. 3	1.25	1.19	1.02

As was seen with mean values, fifth percentile MOR's tend to be higher, for Select Structural than for No. 2 and No. 3 (table 3). However, at the fifth percentile level there appear to be greater-differences between the No. 2 and No. 3 grades for the dry material. The dry-green ratios of fifth percentile MOR values confirm that there is a decided quality influence at the fifth percentile levels, and that the No. 2 and No. 3 grade materials are substantially different from one another in their response to moisture level (table 6). The latter observation is less noticeable for the 2 by 4 lumber. Of particular interest is the consistent reduction in the fifth percentile MOR of 2 by 8, No. 3 lumber with drying. This reduction occurs despite the mild drying schedule used in this study.

It should be cautioned that dry-green ratios of fifth percentiles are much less stable than dry-green ratios of mean values, because small changes in the nonparametric fifth percentile can cause a relatively large change in the dry-green ratio.

Table 6.--Ratio of dry to green values of the fifth percentile nonparametric point[1] estimate of modulus of rupture

Nominal size	Grade	Dry/green fifth percentile ratios: 10 percent moisture content group	15 percent moisture content group	20 percent moisture content group
2 x 4	Select Structural	1.46	1.43	1.13
	No. 2	.96	1.17	1.10
	No. 3	1.10	1.15	1.16
2 x 6	Select Structural	1.46	1.45	1.61
	No. 2	1.36	1.32	1.52
	No. 3	1.11	1.06	1.25
2 x 8	Select Structural	1.31	1.71	1.15
	No. 2	1.11	1.15	1.06
	No. 3	.83	.87	.96

[1]Calculated according to procedures given in ASTM D 2915-80 (1982).

Examination of table 6 indicates that the bulk of the increase in the dry-green ratio of the fifth percentiles occurs in some initial increment of drying, and that past this point there is little increase in strength with further drying. Although the moisture level at which the optimum benefit in terms of fifth percentile MOR is reached varies with size and grade, it would appear there is little benefit in strength to dry to 10 percent. As has been noted by Jessome (1971), this apparent optimum moisture level is probably a result of the contrasting influences of MC on clear wood strength and defect propagation. Initial increases in strength with drying are primarily a result of the increase in clear wood strength with decreasing MC. However, the wood is also shrinking as it dries, and with shrinkage the severity of the defects increases until at some point the gross strength of the wood is actually reduced. A similar phenomenon has also been observed with certain mechanical properties of clear wood (Gerhards 1982) but generally at much lower MCs than were observed in this study.

Moisture Effects for Moment Capacity and Stiffness

Since both MOE and MOR are sensitive to MC, design procedures can be simplified if other parameters are used which are relatively insensitive to changes in moisture level. Possible alternatives are flexural stiffness (El) and moment capacity (RS).

For a constant span, the ability of a beam to resist deflection is indicated by the product of the MOE and the moment of inertia. This product is termed the flexural stiffness. Because MOE tends to increase and the moment of inertia decreases as wood dries, these factors tend to offset one another. In fact, several researchers have found that the effect of drying from the green condition results in minimal or insignificant changes in El (Covington, Fewell 1975; Green 1980; Madsen, Janzen, Zwaagstra 1980). The insensitivity of El to drying appears to be dependent upon the species, the moisture history of the material, and the moisture gradient over the cross section of the piece.

The load that a piece of lumber can support in flexure depends on RS, the product of the MOR and the section modulus. Although few studies have compared RS before and after seasoning, because of offsetting effects, RS may also be relatively insensitive to drying. Johnson (1965) found values of the average dry-green ratio for mean RS of from 1.24 to 1.30 for different grade 2 by 6 Douglas Fir joists. Madsen et al. (1980) showed that there was an interaction between the strength level of several species and the change in RS caused by drying. With the highest quality material, RS was increased significantly with drying to a 12 to 15 percent MC, but further drying caused a decrease in moment capacity. With material of medium or lower capacity, there was little effect of drying on RS except at very low percentiles (which were reduced slightly).

Descriptive statistics for the flexural stiffnesses and moment capacities obtained in this study are shown in table 7. Weibull distributions fit to these data are summarized in Appendix A. Cumulative distribution functions are given in Appendix B.

Mean Moment Capacity

The dry/green ratios of mean RS by grade and size (table 8) are markedly lower than the MOR counterparts in table 5. Nevertheless, the ratios are significantly greater than 1.0 for the three dry groups, indicating the sensitivity of RS to MC. As with MOR, the increases in mean RS with drying are generally less with the lower grades and are not linear with decreasing MC. The magnitude of the increase at the 10 percent moisture level in the Select Structural lumber is on the same order as that shown by Johnson (1965) and Madsen et al. (1980).

fifth Percentile Moment Capacity

Comparison of the dry-green ratios of the 5th percentiles for MOR and RS (tables 6 and 8) indicates that for the two drier groups much of the increase in MOR with drying is offset by the reduction in the section modulus. With the-lower grades, the decrease in section modulus may offset any increase in MOR due to drying. This is particularly noticeable with the lumber that was dried to 10 percent MC.

Mean Flexural Stiffness

The dry-green ratios of mean El are noticeably lower than those of mean MOE (tables 5 and 8). These values are consistent with other studies and indicate that the decrease in moment of inertia almost offsets any increase in MOE and results in a relatively modest improvement in stiffness with drying. In general, these ratios are consistently greater than or near 1.0, which indicates that drying is not injurious for any grade. Indeed, the modest increases are quite similar for all levels of material quality. Except for the 2 by 6's there are no consistent trends that would point to a reduction in mean El with drying below 15 percent.

Comparison of Data Sets

In this section we compare the distributions of each of the 36 grade-size-moisture content combinations to look for similarities and differences. Combining various subsets of the data may be desirable to more clearly delineate general trends in treatment effects or perhaps to achieve certain production or marketing goals. However, if the groups are too dissimilar, combining them may also obscure general trends or mask real discrepancies. Decisions concerning proposed groupings should be approached from two perspectives; statistical and practical. Some information on which to base practical decisions (percentiles, dry-green ratios, etc.) has been presented. Other approaches, such as the use of probabilistic methods to establish adjustment factors, are suggested in the literature (Green 1980). This section will present a statistical evaluation of the differences between groups.

Table 7.--Flexural stiffness and moment capacity of Southern Pine dimension lumber at different equilibrium moisture contents

Nominal size	Grade	Moisture content group	Flexural stiffness’ Mean	Standard deviation	Coeffi-cient of variation	Moment capacity[1] Mean	Standard deviation	Coeffi-cient of variation	Fifth percentile
			—10^6 lb-in.^{2}—		*Pct*	*—10^3 in.-lb.—*		*Pct*	*10^3 in.-lb.*
2 x 4	Select Structural	10	9.80	1.87	19.1	35.57	8.62	24.2	21.36
		15	9.69	2.40	24.8	32.11	6.94	21.6	21.11
		20	8.94	1.90	21.3	28.37	5.72	20.2	17.09
		Green	9.04	2.18	24.1	26.15	6.13	23.4	15.90
	No. 2	10	8.21	2.14	26.1	25.48	10.94	42.9	7.93
		15	8.37	2.50	29.9	24.35	8.65	35.5	9.66
		20	7.21	2.02	28.0	21.36	6.82	31.9	9.43
		Green	7.75	2.15	27.8	20.27	7.09	35.0	8.85
	No. 3	10	7.67	2.02	26.4	22.73	11.24	49.5	7.66
		15	7.86	2.21	28.1	22.74	8.90	39.2	8.15
		20	7.21	1.98	27.4	19.83	6.97	35.2	8.51
		Green	7.41	2.13	28.8	19.10	7.24	37.9	7.53
2 x 6	Select Structural	10	38.54	6.90	17.9	78.46	20.62	26.3	41.17
		15	39.93	7.79	19.5	75.29	18.79	25.0	41.92
		20	37.24	7.41	19.9	67.39	11.39	16.9	48.38
		Green	36.11	8.05	22.3	60.28	14.13	23.4	31.06
	No. 2	10	33.05	7.50	22.7	54.65	26.34	48.2	18.79
		15	35.01	8.65	24.7	56.95	24.33	42.7	19.40
		20	31.26	7.72	24.7	47.45	18.00	37.9	22.37
		Green	31.02	8.62	27.8	44.95	18.98	42.2	15.50
	No. 3	10	31.64	7.37	23.3	53.97	25.16	45.6	15.79
		15	33.68	9.30	27.6	52.81	25.31	47.9	15.31
		20	30.45	8.92	29.3	46.02	18.44	40.1	19.08
		Green	29.62	8.80	29.7	40.91	18.04	44.1	15.52
2 x 8	Select Structural	10	91.28	18.16	19.9	125.35	38.86	31.0	52.91
		15	90.45	16.55	18.3	121.07	27.53	22.7	72.19
		20	84.25	17.52	20.8	97.96	23.69	24.2	49.50
		Green	83.34	17.67	21.2	92.65	24.66	26.6	44.70
	No. 2	10	77.66	16.08	20.7	83.45	41.66	49.9	26.83
		15	75.71	17.34	22.9	87.76	38.88	44.3	30.32
		20	70.45	17.96	25.5	70.66	30.15	42.7	28.81
		Green	69.08	17.34	25.1	67.44	26.40	39.1	27.78
	No. 3	10	76.71	25.54	33.3	90.80	49.54	54.5	22.53
		15	76.38	20.01	26.2	85.90	39.93	46.5	24.03
		20	68.34	20.71	30.3	74.18	31.01	41.8	27.36
		Green	70.92	19.93	28.1	73.00	30.85	42.3	29.47

[1]Original data contained three significant digits. Additional digits retained to permit further computations with minimum round-off error.

Table 8.--Ratio of dry to green properties for moment capacity and mean flexural stiffness

Nominal size	Grade	Mean flexural stiffness			Moment capacity					
					10 percent		15 percent		20 percent	
		10 percent	15 percent	20 percent	Mean	NPE[1]	Mean	NPE[1]	Mean	NPE[1]
2 x 4	Select Structural	1.08	1.07	0.99	1.36	1.34	1.23	1.33	1.08	1.07
	No. 2	1.06	1.08	.93	1.25	.90	1.20	1.09	1.05	1.07
	No. 3	1.04	1.06	.97	1.15	1.02	1.15	1.08	1.00	1.13
2 x 6	Select Structural	1.07	1.11	1.03	1.30	1.33	1.25	1.35	1.12	1.56
	No. 2	1.07	1.13	1.01	1.22	1.21	1.27	1.25	1.06	1.44
	No. 3	1.07	1.14	1.03	1.32	1.02	1.29	.99	1.12	1.23
2 x 8	Select Structural	1.10	1.09	1.01	1.35	1.18	1.31	1.61	1.06	1.11
	No. 2	1.12	1.10	1.02	1.24	.97	1.30	1.09	1.05	1.04
	No. 3	1.08	1.08	.96	1.24	.76	1.18	.82	1.02	.93

[1]NPE = Nonparametric estimate of the fifth percentile (ASTM D 2915-80, 1982).

Three tests were performed to test the hypothesis that there was no difference between groups. The equivalency of the overall property distributions was evaluated using the. Kolomogorov-Smirnov two-sample test statistic (Conover 1980). A comparison of mean values was conducted by first computing an analysis of variance (ANOVA) for each variable and then conducting a multiple comparison of the groups using a series of modified two-sample t-tests (Miller 1981). The t statistic was calculated in two ways: (1) using the overall variance from the ANOVA and (2) using the individual variances for the two groups involved. Finally, a comparison of selected p^{th} percentiles was conducted using a modified median (chi-square) test with continuity correction (Conover 1980). With the sample sizes used in this study, the modified median test lacks power (will tend to indicate that percentiles are equal when in fact they may not be) when applied to percentiles in the tails of the distribution. This is because of the scarcity of observations in the tail regions.

A summary of the results for these tests is presented in table 9 for MOR and MOE and in table 10 for EI and RS. If none of the groups could be considered equal ($p < 0.2$ for each comparison) then the entry is "none equal." Otherwise the groups are listed. The ordering has no importance in the case of distributions. For means and fifth percentiles the groups are ordered from high to low. If two groups share a common underline, there is insufficient evidence for them to be considered different, $p \geqslant 0.2$. If groups do hot share a common underline they cannot be considered equal, $p < 0.2$.

Modulus of Rupture

The results presented in table 9 suggest that No. 2 and No. 3 grades may be combined for many moisture content-size combinations. This conclusion is consistent with the previous discussion of moisture effects on mean MOR. The lack of power of the modified median test for fifth percentile MOR is evident, however, when one compares the potential groupings listed in table 9 with the MOR's shown in table 3. For example, comparing No. 2 and No. 3 grades at the 10 percent MC level, fifth percentile estimates that differ by 20 to 25 percent would still be grouped. This estimate of power for the modified median test is contrasted with the t-test used for the mean values where a difference of approximately 10 percent is required in order to reject equality. The results also suggest that, in general, it is not wise to lump sizes or MC levels when considering MOR.

The effect of MC on the pattern of the MOR cumulative frequency distributions at the four MC levels for No. 2 and No. 3 grade lumber is shown in figure 3. The influence of MC is not uniform over the entire distribution. Rather, drying had the greatest impact on the highest quality lumber and the least impact on the lowest quality. As can be seen from the individual plots, Appendix figure B1, this observation is true for all grade-size combinations.

Table 9.--Modulus of rupture and modulus of elasticity: Groups for which equality cannot be rejected at p = 0.2.

Basis of comparison			Modulus of rupture			Modulus of elasticity	
Nominal size	Grade	Moisture content group	Distribution	Mean	Fifth percentile	Distribution	Mean
				MOISTURE CONTENT			
2 x 4	Select Structural		none equal[1]	none equal	10 15 20 green[2]	10 15 20 green	none equal
	No. 2		none equal	none equal	15 20 green 10	10 15 20 green	10 15 green 20
	No. 3		10 15 20 green	10 15 20 green	20 15 10 green	10 15 20 green	10 15 20 green
2 x 6	Select Structural		none equal	none equal	20 10 15 green	10 15 20 green	10 15 20 green
	No. 2		10 15 20 green	15 10 20 green	20 10 15 green	10 15 20 green	15 10 20 green
	No. 3		10 15 20 green	10 15 20 green	20 10 15 green	10 15 20 green	15 10 20 green
2 x 8	Select Structural		none equal	none equal	15 10 20 green	none equal	none equal
	No. 2		10 15 20 green	15 10 20 green	15 10 20 green	10 15 20 green	none equal
	No. 3		none equal	10 15 20 green	green 20 15 10	10 15 20 green	10 15 20 green
				SIZE			
	Select Structural	10	none equal	none equal	none equal	4 6 8	4 6 8
		15	none equal	none equal	4 6 8	4 6 8	6 4 8
		20	none equal	none equal	6 4 8	4 8	6 4 8
		Green	none equal	none equal	4 6 8	6 4 8	6 4 8
	No. 2	10	4 6 8	none equal	4 6 8	4 6 8	6 4 8
		15	4 6 8	none equal	4 6 8	4 8 6	none equal
		20	none equal	none equal	4 6 8	4 8 6	6 8 4
		Green	none equal	none equal	4 8 6	4 6 8	6 4 8
	No. 3	10	4 6 8	4 6 8	none equal	4 6 8	8 6 4
		15	4 6 8	4 6 8	4 6 8	4 6 8	6 8 4
		20	none equal	none equal	4 6 8	4 6 8	6 4 8
		Green	4 6 8	4 6 8	4 8 6	4 6 8	4 6 8
				GRADE			
2 x 4		10	none equal	none equal	SS 2 3	none equal	none equal
2 x 6			SS 2 3	SS 2 3	SS 2 3	SS 2 3	SS 2 3
2 x 8			none equal	SS 2 3	SS 2 3	none equal	SS 2 3
2 x 4		15	SS 2 3	none equal	SS 2 3	SS 2 3	none equal
2 x 6			none equal	SS 2 3	none equal	SS 2 3	SS 2 3
2 x 8			SS 2 3	SS 2 3	SS 2 3	SS 2 3	SS 2 3
2 x 4		20	none equal	none equal	SS 2 3	SS 2 3	SS 2 3
2 x 6			SS 2 3	SS 2 3	none equal	SS 2 3	SS 2 3
2 x 8			none equal	SS 2 3	SS 2 3	SS 2 3	SS 2 3
2 x 4		Green	SS 2 3	SS 2 3	none equal	SS 2 3	SS 2 3
2 x 6			SS 2 3	none equal	SS 2 3	SS 2 3	SS 2 3
2 x 8			SS 2 3	SS 2 3	SS 2 3	SS 2 3	SS 2 3

[1]None equal = for each combination of two groups, equality was rejected p < 0.2.

[2]Groups sharing a common underline cannot be considered different p ⩾ 0.2. Groups which do not share a common underline, p < 0.2. For distributions, order of groups does not represent order of distribution. For means and fifth percentile, groups are ordered from high to low.

Table 10.--Moment capacity and flexural stiffness: Groups for which equality cannot be rejected at p = 0.2 (moisture content)

Basis of comparison		Moment capacity, RS			Flexural stiffness, EI	
Nominal size	Grade	Distribution	Mean	Fifth percentile	Distribution	Mean
2 x 4	Select Structural	none equal[1]	none equal	10 15 20 green[2]	10 15 20 green	10 15 green 20
	No. 2	10 15 20 green	10 15 20 green	15 20 green 10	10 15 20 green	15 10 green 20
	No. 3	10 15 20 green	15 10 20 green	20 15 green 10	10 15 20 green	15 10 green 20
2 x 6	Select Structural	none equal	10 15 20 green	20 15 10 green	10 15 20 green	15 10 20 green
	No. 2	10 15 20 green	10 15 20 green	20 15 20 green	10 15 20 green	15 10 20 green
	No. 3	10 15 20 green	10 15 20 green	20 green 10 15	10 15 20 green	15 10 20 green
2 x 8	Select Structural	none equal	10 15 20 green	15 10 20 green	10 15 20 green	10 15 20 green
	No. 2	10 15 20 green	15 10 20 green	15 20 green 10	10 15 20 green	10 15 20 green
	No. 3	10 15 20 green	10 15 20 green	green 20 15 10	10 15 20 green	10 15 green 20

[1]None equal = for each combination of two groups, equality was rejected p < 0.2.

[2]Groups sharing a common underline can not be considered different p ≥ 0.2. Groups which do not share a common underline, p < 0.2. For distributions, order of groups does not represent order of distribution. For means and fifth percentile groups are ordered high to low.

Drying the No. 2 and No. 3 grade lumber from green to 20 percent generally results in a slight increase in MOR for a significant proportion of the distribution (fig. 3). However, for some grade-size combinations, especially 2 by 8's, there is no increase in the lower end of the distribution (fig. B1). Drying from 20 to 15 percent had a pronounced effect on the stronger samples, with the effect gradually decreasing to the point that there was no effect on the weaker pieces (below about the 20th to 30th percentile). Further drying to 10 percent generally caused a relatively moderate increase in the MOR of the stronger pieces, but was injurious to much of the lower half of the distribution (fig 3). Even in the upper end of the distribution, drying from 15 to 10 percent MC was of little benefit for some grade-size combinations (table 11, figs. B1 and B5).

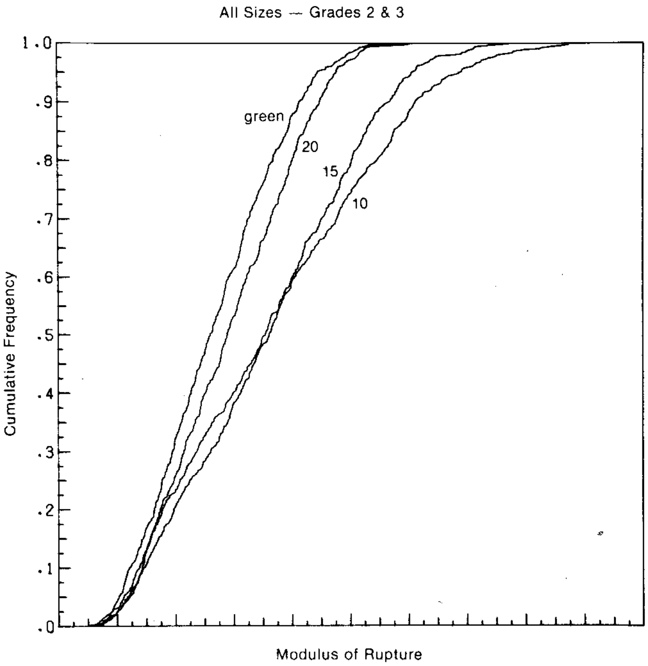


Figure 3.—Form of the cumulative frequency distributions of MOR for No. 2 and No. 3 grade lumber combined. (ML84 5319)

Table 11.--Percent change in properties in drying from 15 to 10 percent moisture content[1]

Property	Nominal size	Grade	Percentile level						
			5	10	25	50	75	90	95
MOR	2 x 4	Select Structural	2.5	14.6	7.9	11.5	18.3	17.0	15.0
		No. 2	-17.8	-14.0	-3.9	4.1	14.6	16.2	18.3
		No. 3	-3.8	-11.3	-14.8	-6.9	8.1	20.9	12.6
	2 x 6	Select Structural	0.8	-4.8	7.7	6.6	9.1	9.9	12.3
		No. 2	3.4	-0.7	-14.7	-5.1	-1.0	2.3	9.3
		No. 3	4.7	27.5	10.7	11.0	0.5	5.9	5.0
	2 x 8	Select Structural	-23.5	-16.0	-1.8	9.7	16.1	16.3	16.0
		No. 2	-3.1	-4.7	-3.1	-9.2	2.7	4.3	3.0
		No. 3	-4.4	-18.9	-11.7	15.0	19.9	15.4	12.4
MOE	2 x 4	Select Structural	22.8	16.0	10.9	6.2	1.0	-3.1	-1.1
		No. 2	10.4	4.4	6.3	5.0	3.6	-4.8	-3.5
		No. 3	10.3	2.8	-4.0	3.0	-1.0	4.9	-0.4
	2 x 6	Select Structural	-1.0	9.7	5.7	1.5	-1.6	-0.6	-0.2
		No. 2	15.6	7.2	-0.8	-3.9	-6.9	0.0	-3.1
		No. 3	20.8	10.8	-1.4	-1.7	-2.4	-6.8	-4.1
	2 x 8	Select Structural	4.7	1.7	5.8	5.6	3.4	6.8	9.5
		No. 2	5.7	8.2	7.0	6.9	9.0	0.8	3.7
		No. 3	-9.5	-3.0	0.0	-0.5	11.2	14.5	12.4

[1]Percent change = 100 x (value at 15 percent-value at 10 percent) ÷ value at 15 percent.

With Select Structural 2 by 4 lumber, drying from the green condition increased the strength almost uniformly throughout the distribution (fig. 4). This was true for 2 by 6 and 2 by 8 lumber also, and contrasts markedly with the general trend for No. 2 and No. 3 grade lumber. As with the No. 2 and No. 3 grade, the biggest benefit from dry Select Structural lumber appears to occur with drying from 20 to 15 percent. Drying from 15 to 10 percent MC increases the MOR of the 2 by 4 Select Structural lumber markedly for all but the lower 5 percent of the strength distribution (table 11). With 2 by 6 and 2 by 8 lumber the improvement was generally limited to the upper 70 to 85 percent of distribution with the lower 20 percent of the 2 by 8 lumber showing a noticeable decrease in strength with drying from 15 to 10 percent (figs. B1 and B5).

The dry-green ratios for drying to 15 percent for the individual grades and sizes is illustrated in figure 5 as a function of position in the strength distribution. Here the three-parameter Weibull distribution (Appendix A) was first fit to the MOR data in order to smooth the distributions (dry-green ratio plots for individual grade-size combinations are shown in fig. B7). At the median (50th percentile) the ratio is between 1.28 and 1.40 and does not change greatly down to about the 35th percentile.

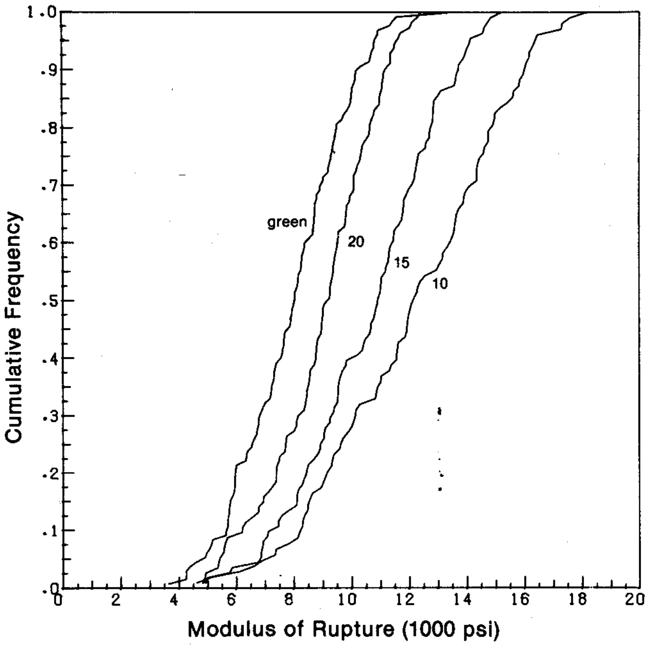


Figure 4.—Cumulative frequency distributions for MOR of 2 by 4 Select Structural lumber. (ML84 5320)

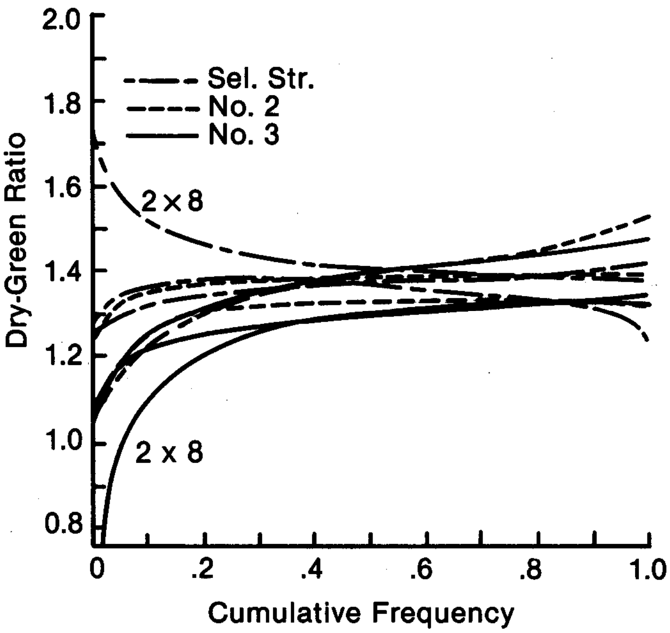


Figure 5.—Effect of position in the MOR distributions on the dry-green ratio of lumber dried to 15 percent moisture content (ratios obtained from fitted three-parameter Weibull distributions). (ML84 5261)

The results presented previously indicate that drying lumber from 15 to 10 percent may have a detrimental effect on the MOR of lumber in the lower half of the strength distribution for No. 2 and No. 3 grade material, and may be of limited benefit for Select Structural. A considerable savings in reduced drying costs and reduced loss of quality could be obtained by lumber producers and consumers if lumber were only dried to an average MC of 15 percent. It is cautioned, however, that increased strength is not the primary reason for drying lumber. Market acceptance of lumber dried to a particular MC must also be considered. The number of drying-related defects in a board tend to increase with decreasing MC. If lumber is not carefully dried to a MC low enough for the intended use, then the cost of any additional degrade will either be borne by consumers or they may select an alternative species. Changes in drying practices should therefore only be made after careful consideration of all possible implications of the change.

The crossing of probability distribution functions in the lower quarter of the strength distribution presents an interesting dilemma for code authorities. Current deterministic design procedures would suggest that moisture adjustment factors should be based solely on the ratios of fifth percentile strength estimates. Yet, entirely different decisions might be reached on adjustment factors if the ratios of strengths at slightly higher (or lower) percentile levels were considered. A more realistic estimate of structural performance might be obtained if probabilistic procedures were used. However, it is not apparent that such procedures will be adopted for lumber in the next few years. It has been suggested that probabilistic considerations could be used to obtain the adjustment factors for use in a deterministic design format (Green 1980). This would be accomplished by superimposing the same load distribution on two material property frequency distributions obtained for different moisture control levels, and then determining what single factor one property distribution could be multiplied by in order to obtain the same probability of failure as calculated for the other property distribution. This “shift factor” would be the MC adjustment factor used in design codes. Work is currently in progress to define appropriate load distributions for use in such reliability analyses (Thurmond, Woeste, Green 1983).

Modulus of Elasticity

The data in table 9 indicate that MOE is less sensitive to size and grade effects than is MOR. In all cases, the mean MOE of Select Structural was higher than that of No. 2 or No. 3 (table 3). In most cases the MOE of No. 2 is higher than No. 3, but the actual difference (which ranges from a 2.4 percent reduction in the MOE of No. 2 versus that of No. 3 for green 2 by 8’s to an 8 percent increase for 2 by 4’s at 10 percent moisture content) was not significant. In many cases the differences in MOE between sizes was also not significant.

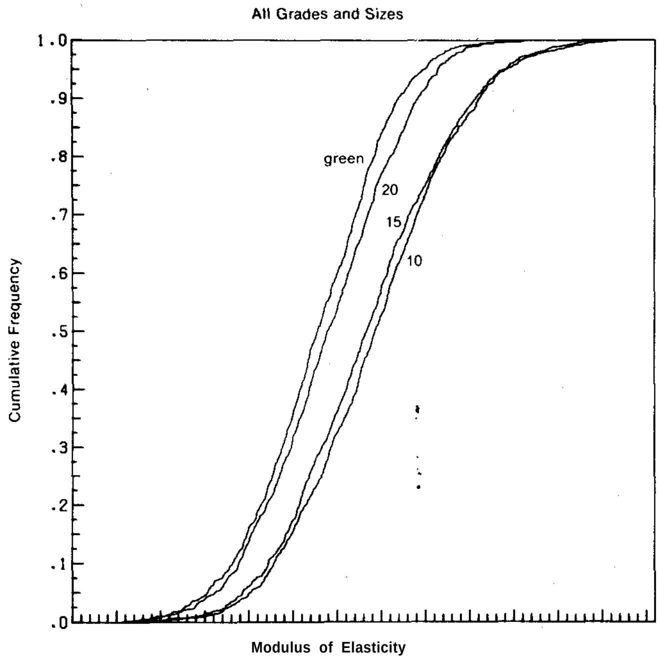


Figure 6.—Form of the cumulative frequency distributions of MOE for target moisture contents of 10, 15, and 20 percent, all grades and sizes combined. (ML84 5321)

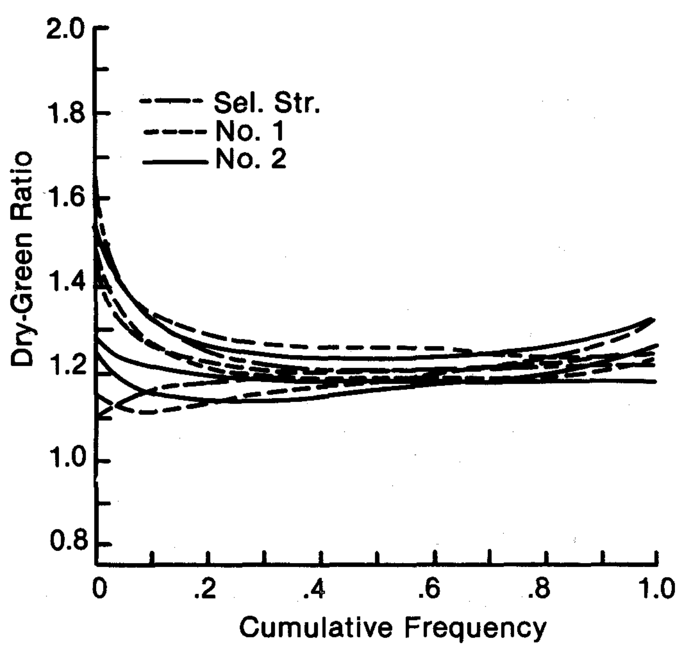


Figure 7.—Effect of position in the MOE distribution on the dry-green ratio of lumber dried to 15 percent moisture content (ratios obtained from fitted three-parameter Weibull distribution). (ML84 5262)

In general, drying improves the MOE of the lumber nearly uniformly over the entire range of distribution (fig. 6). Again, the largest increase is for drying between 20 and 15 percent, with the increases from green to 20 percent and from 15 to 10 percent being noticeably less. Drying from 15 to 10 percent MC is not always advantageous, especially for No. 3 grade lumber (figs. B2 and B6, table 11).

The effect of drying on MOE is much less dependent on the position in the distribution than it is for MOR. This can be seen with the dry-green ratio (obtained from Weibull fits) for lumber dried to a MC of 15 percent (fig. 7). These results are reasonable because MOE is more of a “whole piece” property rather than a “point” property. That is, the ultimate strength in bending is generally either compression-face or tension-face oriented and is dependent on the strength of the weakest section in the area of maximum moment. However, MOE is a composite of all the variation in elasticity along the piece of lumber. Therefore, it is reasonable to find that MOE is less dependent on the action of drying on a critical defect or defects, hence the fairly uniform effect along the entire distribution of elastic moduli. Dry-green ratio plots for individual grade-size combinations are shown in figure B8.

Moment Capacity and Stiffness

As would be expected, the form of cumulative frequency distributions for RS and EI are virtually identical to those given for MOR and MOE (figs. 3,6). As previously noted, however, RS and EI are less sensitive than are MOR and MOE (respectively) to changes in MC (table 10). Cumulative frequency distributions for RS and EI are shown in figures B5 and B6.

Conclusions

Based on the study results we conclude that:

1. In general, drying increases the flexural properties of Southern Pine dimension lumber.
2. Improvements in MOR and MOE with drying are significant for Select Structural lumber at virtually all levels of the cumulative frequency distribution. The magnitude of the increase for mean MOE and fifth percentile MOR for Select Structural lumber appears to exceed that assumed in ASTM standard D245-81 for lumber dried to an equilibrium MC of 15 percent.
3. The degree of improvement in strength as lumber dries decreases as lumber quality decreases and width increases. For lower grades and wider widths, the 25 percent increase in fifth percentile MOR assumed in D245-81 appears excessive.
4. The effect of MC on MOE is relatively independent of lumber size and quality.
5. Drying lumber to an average MC less than 15 percent cannot usually be justified on the basis of improvements in flexural strength and stiffness.

Questions as to the applicability of these data to other species and other failure modes will be addressed in subsequent publications. Future reports will also present analytical models and probabilistic procedures for adjusting in-grade data that might also be considered for adoption by engineering code authorities. Until this series of reports is complete the results of this study should not be incorporated into engineering design codes.

Literature Cited

American Society for Testing and Materials. Establishing structural grades and related allowable properties for visually graded lumber. ASTM D 245-81. Philadelphia, PA; 1982.

American Society for Testing and Materials. Standard method for evaluating allowable properties for grades of structural lumber. D 2915-80. Philadelphia, PA; 1982.

American Society for Testing and Materials. Standard test methods for specific gravity of wood and wood-base materials. ASTM D 2395-69. Philadelphia, PA; 1982.

American Society for Testing and Materials. Static tests of timbers in structural sizes. ASTM D 198-76. Philadelphia, PA; 1982.

Anderson, T. W.; Darling D. A. A test of goodness of fit. J. Am. Stat. Assoc. 49: 765-769; 1954.

Brynildsen, O. Moisture effect on bending strength and stiffness of European spruce. Norsk Tre teknisk Institut, Oslo, Norway. Paper prepared for meeting of Working Party CIB W18/IUFRO S5, 02-03, London; 1977.

Cline, M.; Heim, A. L. Tests of structural timbers. Bull. No. 108. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1912.

Conover, W. J. Practical nonparametric statistics. 2nd ed. John Wiley and Sons, New York, NY; 1980.

Covington, S. A.; Fewell, R. A. The effect of changes in moisture content on the geometrical properties, modulus of elasticity and stiffness of timber. Current Pap. CP 21-75. Princes Risborough, England: Build. Res. Estab.; 1975.

DeBonis, A. L.; Woeste, F. W.; McLain, T. E. Rate of loading influence on southern pine 2 x 4's in bending. Forest Prod. J. 30(11): 34-37; 1980.

Filliben, J. J. The probability plot correlation coefficient test for normality. Technometrics 17(1): 111-117; 1975.

Galligan, W. L.; Green, D. W.; Gromala, D. S.; Haskell, J. H. Evaluation of lumber properties in the United States and their application to structural research. Forest Prod. J.30(10): 45-51; 1980.

Gerhards, C. C. Four-inch southern pine lumber: seasoning factors for modulus of elasticity and modulus of rupture. Forest Prod. J. 18(11): 27-35; 1968.

Gerhards, C. C. Further report on seasoning factors for modulus of elasticity and modulus of rupture. Forest Prod. J. 20(5): 40-44; 1970.

Gerhards, C. C. The effect of moisture content and temperature on the mechanical properties of wood: an analysis of immediate effects. Wood and Fiber 14(1): 4-36; 1982.

Green, D. W. Adjusting the static strength of lumber for changes in moisture content. In: Proceedings, Workshop on how the environment affects lumber design: assessments and recommendations; Madison, WI: Forest Prod. Lab.; 1980. p. 86-105.

Hoffmeyer, P. Moisture content-strength relationship for spruce lumber subjected to bending, compression and tension along the grain. In: Proceedings, IUFRO wood engineering group meeting; Vancouver, BC; p. 72-91; 1978.

Jessome, A. P. The bending strength of lumber in structural sizes. Publ. No. 1305. Department of Environment, Canadian Forest Service, Ottawa; 1971.

Johnson, J. W. Relationship among moduli of elasticity and rupture; seasoned and unseasoned coast-type Douglas-fir and seasoned western hemlock. In: Proceedings, Second symposium on nondestructive testing of wood, Spokane, WA; 1965; p. 419-549.

Littell, R. C.; McClave, J. T.; Offen, W. W. Goodness-of-fit tests for the two parameter Weibull distribution. Commun. Stat.--Simul. Comput. B8(3): 257-269; 1979.

Madsen, B. Moisture content-strength relationship for lumber subjected to bending. Canadian J. Civil Eng. 2(4): 466-473; 1975.

Madsen, B.; Barrett, J. D. Time-strength relationship for lumber. Rep. No. 13. Vancouver, BC: Department of Civil Engineering, Structural Research Service, University British Columbia; 1976.

Madsen, B.; Janzen, W.; Zwaagstra, J. Moisture effects in lumber. Rep. No. 27. Vancouver, BC: Department of Civil Engineering, Structural Research Service, University British Columbia; 1980.

Miller, R. G., Jr. Simultaneous statistical inference. Springer-Verlag, New York, NY; 1981.

Orosz, I. Some nondestructive parameters for prediction of strength of structural lumber. Research Paper FPL 100. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1968.

SAS Institute. Statistical Analysis System (SAS) users guide. Raleigh, NC; 1979.

Snedecor, G. W.; Cochran, W. O. Statistical methods. 6th ed. Iowa State University Press, Ames, IA; 1967.

Southern Pine Inspection Bureau. Grading rules. Pensacola, FL; 1977.

Spencer, R. Rate of loading effect in bending for Douglas-fir lumber. Vancouver, BC: Department of Civil Engineering, Univ. British Columbia; 1979.

Stephens, M. A. EDF statistics for goodness of fit and some observations. Journal of the American Statistical Association. 69(347):730-735. 1974.

Stephens, M. A. Goodness of fit for the extreme value distribution. Biometrika, 64(3):583-588; 1977.

Stevens, W. C. The transverse shrinkage of wood. Forest Prod. J. 13(9): 386-389; 1963.

Thurmond, M. B.; Woeste, F. E.; Green, D. W. Roof loads for reliability analysis of lumber properties data. Wood and Fiber Science 15(4): 278-297; 1983.

Warren, W. G.; Madsen, B. Computer-assisted experimental design in forest products research: a case study based on testing the duration of load effect. Forest Prod. J. 27(3): 45-50; 1977.

Wilson, F. J. The effect of moisture content on the flexural strength and stiffness of southern pine dimension lumber. M.S. thesis. Blacksburg, VA: Department of Forest Products, Virginia Polytechnic Inst. and State Univ.; 1981.

Wilson, T.R.C. Strength-moisture relations for wood. Tech. Bull. No. 282. U.S. Department of Agriculture; 1932.

Appendix A
Distributional Form of the Flexural Data

Normality

The data were tested for normality using the one sample Kolmogorov-Smirnov goodness-of-fit test (KS) (Conover 1980; SAS Institute 1979) and the probability plot correlation coefficient test (PPC) (Filliben 1975). The PPC test is more powerful against a range of distribution alternatives (Filliben 1975) and is probably more sensitive to the data points in the tails of the distribution. The KS test, however, is perhaps better known to engineers and, with the sample sizes used in this study (77 to 141) should have sufficient power to detect deviations from normality.

The data were further examined to determine if any lack of normality was a result of skewness (lack of symmetry) or kurtosis (degree of flatness). Because the sample sizes used in this study are less than required to assure that the skewness and kurtosis coefficients are normally distributed, critical values for these coefficients were obtained from table A6 of Snedecor and Cochran (1967). For 20 of the 36 MOR distributions the PPC test does not reject normality[1] (table A1). A similar conclusion is drawn for 23 of the 36 distributions using the KS test. From the opposite perspective, in 44 percent of the cases there was reason to reject normality using the PPC test ($p < 0.05$). In general, the distributions tended to deviate from normality more as the specimen width increased and the grade decreased. Trends with moisture content were not consistent.

Of the 16 cases where the PPC test rejected normality, kurtosis was significant for 8; in 5, both kurtosis and skewness were significant. In only three cases was skewness the sole cause of rejection of normality. Skewness tended to be more important for Select Structural lumber (the distributions tended to be left skewed)[2] while kurtosis was more important for No. 2 and No. 3 grades (the distributions tended to have more observations in the upper and lower tails than would be expected for a normal distribution). If confirmed by the more extensive studies being conducted in the in-grade testing program (Galligan et al. 1980), the occurrence of left skewed strength distributions for Select Structural lumber would make the log-normal distribution less desirable for reliability studies because log-normal distributions are right skewed.

For MOE, normality was seldom rejected. The acceptance of the normality hypothesis for MOE and its rejection for MOR are in agreement with numerous similar conclusions in the literature.

The results of normality tests for flexural stiffness and moment capacity are similar, respectively, to the results for MOE and MOR.

Weibull Distribution

Tables A2 through A5 present the estimated parameters for the three-parameter Weibull distribution fit to the data using a maximum likelihood estimation procedure.[3] Tables A6 through A9 present the estimates for the two-parameter Weibull distribution. This distribution was selected because of its flexibility in fitting both right-skewed (shape parameters less than about 3.6) and left-skewed (shape parameters greater than about 3.6) data.

The "goodness of fit" of the two- and three-parameter Weibull distribution to the MOR and MOE data was evaluated using the Anderson-Darling, A^2, test (1954) and the KS test (Conover 1980). The A^2 test has been shown to have reasonably good power against a number of alternative distributions (Littell, McClave, Offen 1979; Stephens 1974, 1977). The A^2 test is slightly more sensitive than the KS test to lack of fit in the tails of the distribution.

In most cases the three-parameter Weibull distribution fit the MOR and MOE data quite well (figs. A1 and A2). The fit was generally not good for the MOR of the dry 2 x 8's. In 7 of 9 cases, the A^2 statistic was significant (indicates lack of fit) at the $p = 0.05$ level for dry 2 x 8's (table A10). Visual inspection of these distributions indicated that probably no other standard distribution would provide a better fit (fig. A3). The KS test did not indicate a lack of fit for any of the distributions and is thus not given in the table. This confirms the known lack of power of the one sample KS test for identifying lack of fit with small to moderate sample sizes. As expected the two-parameter Weibull distribution did not fit the data quite as well as did the three-parameter distributions (table Al 1).

---

[1] In this discussion, "does not reject normality" is taken to mean that the p value for testing the null hypothesis of normality (by whatever test: PPC, skewness, kurtosis, ...) is larger than 0.05.

[2] A left-skewed distribution has a relatively long tail toward decreasing values of MOR.

[3] Warren, W. G. Program for maximum likelihood estimation of Weibull parameters. Personal communication to Forest Prod. Lab., Madison, WI; 1978.

Table A1.--Assessment of normality for modulus of rupture and modulus of elasticity

Grade	Nominal size	Moisture content group	Modulus of rupture: KS[1]	PPC[2]	Skewness[3]	Kurtosis[4]	Modulus of elasticity: KS	PPC	Skewness	Kurtosis
Select Structural	2 x 4									
		10	—[5]	—	—	*[6]	—	—	—	—
		15	—	—	—	—	—	—	—	—
		20	—	—	*	—	—	—	—	—
		Green	—	—	—	—	—	—	—	—
	2 x 6									
		10	—	*	*	—	—	—	—	—
		15	—	—	*	—	—	—	—	—
		20	*	*	**[7]	**	—	*	**	—
		Green	*	*	**	—	*	—	*	—
	2 x 8									
		10	—	—	—	*	—	—	—	—
		15	—	—	—	—	—	—	—	—
		20	*	*	**	—	—	—	—	—
		Green	—	—	—	—	—	—	*	—
No. 2	2 x 4	10	—	—	—	*	—	—	—	—
		15	—	—	—	—	—	*	*	—
		20	*	*	—	**	—	—	—	—
		Green	—	—	—	*	—	—	—	—
	2 x 6	10	*	*	*	*	*	—	*	—
		15	—	—	—	*	—	—	—	—
		20	—	*	—	**	—	—	—	—
		Green	—	—	—	—	—	—	—	—
	2 x 8	10	*	*	—	**	—	—	—	—
		15	*	*	—	**	—	—	—	—
		20	*	*	*	**	—	—	—	—
		Green	—	—	—	—	—	—	—	—
No. 3	2 x 4	10	*	*	*	*	—	—	*	—
		15	—	—	—	*	—	—	*	—
		20	—	—	—	—	*	—	—	—
		Green	—	—	—	**	—	—	—	—
	2 x 6	10	—	—	—	—	—	—	*	—
		15	—	*	—	**	—	—	—	—
		20	—	—	—	**	—	—	—	—
		Green	—	—	—	—	—	—	—	—
	2 x 8	10	*	*	—	**	—	—	—	—
		15	*	*	—	**	—	—	—	*
		20	*	*	—	**	—	—	—	—
		Green	*	*	*	*	—	—	—	—

[1]KS: Kolmogorov-Smirnov goodness of fit test (Miller 1981; SAS Institute 1979).

[2]PPC: Probability plot correlation test (Filliben 1975).

[3]Lack of symmetry (Snedecor and Cochran, 1967).

[4]Degree of flatness (Snedecor and Cochran, 1967).

[5]— indicates there is no reason to reject normality with $p > 0.05$.

[6]* indicates there is reason to reject normality with $0.01 < p \leqslant 0.05$.

[7]** indicates there is reason to reject normality with $p \leqslant 0.01$.

Table A2.— Three-parameter Weibull distribution for the modulus of rupture of Southern Pine lumber at various moisture contents[1]

Nominal size	Grade	Moisture content class	Estimated Weibull parameters			Weibull 5 percent point			5 percent tolerance limit, 95 percent confidence	
			Shape	Scale	Location	Estimate	95 percent lower confidence limit	95 percent upper confidence limit	Weibull	Nonparametric
In.		Pct	10^3 lb/in.^{2}							
2 x 4	Select Structural	10	4.659	13.322	0.000	7.042	6.007	8.076	6.174	5.127
		15	5.027	11.065	.508	6.636	5.814	7.459	5.946	4.982
		20	5.853	9.721	.000	5.852	5.216	6.489	5.318	4.895
		Green	3.248	6.092	2.496	4.938	4.499	5.377	4.570	4.267
2 x 4	No. 2	10	2.270	9.021	.659	3.097	2.329	3.864	2.453	2.272
		15	3.051	8.982	.000	3.393	2.684	4.102	2.798	2.139
		20	3.587	7.530	.000	3.290	2.702	3.878	2.796	2.137
		Green	2.581	5.763	1.060	2.883	2.437	3.329	2.509	2.193
2 x 4	No. 3	10	1.742	7.408	1.064	2.411	1.945	2.876	2.020	1.563
		15	2.503	7.806	.560	2.943	2.260	3.625	2.370	2.141
		20	2.785	6.357	.604	2.791	2.217	3.366	2.309	1.611
		Green	2.567	5.791	.675	2.496	1.924	3.067	2.016	1.905
2 x 6	Select Structural	10	4.466	11.696	.000	6.015	5.290	6.740	5.406	4.031
		15	4.726	10.803	.000	5.762	5.071	6.453	5.182	3.453
		20	7.116	9.059	.000	5.967	5.511	6.424	5.584	4.169
		Green	5.204	7.920	.000	4.475	4.030	4.921	4.101	3.166
2 x 6	No. 2	10	1.745	6.924	1.215	2.477	2.066	2.887	2.132	1.788
		15	2.186	7.481	.853	2.776	2.230	3.322	2.318	2.254
		20	2.142	5.175	1.375	2.668	2.338	2.998	2.391	2.202
		Green	2.127	5.213	.813	2.103	1.741	2.465	1.799	1.506
2 x 6	No. 3	10	2.091	7.700	.437	2.297	1.674	2.919	1.774	1.079
		15	1.761	6.481	1.102	2.302	1.822	2.782	1.899	1.644
		20	2.226	5.475	.912	2.354	1.897	2.810	1.971	1.454
		Green	1.733	4.181	1.205	1.958	1.643	2.274	1.693	1.500
2 x 8	Select Structural	10	3.651	10.587	.000	4.693	3.999	5.388	4.110	3.206
		15	3.756	7.647	1.979	5.447	4.926	5.967	5.010	4.305
		20	4.879	7.556	.000	4.110	3.672	4.548	3.742	2.843
		Green	4.337	6.882	.000	3.469	3.026	3.913	3.097	2.493
2 x 8	No. 2	10	1.554	5.453	1.340	2.147	1.836	2.459	1.886	1.626
		15	1.928	6.023	1.060	2.351	1.904	2.798	1.975	1.824
		20	1.907	4.389	1.086	2.011	1.729	2.292	1.775	1.815
		Green	1.999	3.833	1.164	2.031	1.761	2.301	1.805	1.646
2 x 8	No. 3	10	1.393	6.219	1.177	1.914	1.574	2.253	1.629	1.306
		15	2.055	6.466	.547	2.071	1.523	2.619	1.611	1.124
		20	2.239	5.157	.657	2.026	1.537	2.515	1.615	1.325
		Green	1.808	4.096	1.288	2.080	1.783	2.378	1.831	1.472

[1]Table A10 indicates the degree of fit of the three-parameter Weibull distribution to the data.

Table A3.—Three-parameter Weibull distribution for the modulus of elasticity of Southern Pine lumber at various moisture contents[1]

Nominal size	Grade	Moisture content class	Estimated Weibull parameters			Weibull 50 percent point			50 percent tolerance limit, 95 percent confidence	
			Shape	Scale	Location	Estimate	95 percent lower confidence limit	95 percent upper confidence limit	Weibull	Nonparametric
In.		*Pct*				10^6 lb/in.^{2}				
2 x 4	Select Structural	10	4.272	1.672	0.432	1.967	1.883	2.052	1.896	1.825
		15	3.701	1.796	.239	1.866	1.767	1.965	1.783	1.757
		20	4.234	1.441	.307	1.629	1.556	1.703	1.567	1.551
		Green	3.925	1.444	.234	1.549	1.478	1.619	1.489	1.470
2 x 4	No. 2	10	3.270	1.501	.273	1.615	1.517	1.713	1.533	1.496
		15	2.910	1.520	.233	1.572	1.471	1.674	1.487	1.439
		20	4.032	1.435	.000	1.310	1.236	1.384	1.248	1.244
		Green	3.861	1.412	.046	1.331	1.255	1.406	1.267	1.218
2 x 4	No. 3	10	2.438	1.107	.517	1.470	1.375	1.564	1.390	1.366
		15	2.390	1.137	.482	1.457	1.356	1.558	1.372	1.321
		20	2.682	1.014	.392	1.277	1.190	1.363	1.204	1.197
		Green	2.890	1.075	.307	1.254	1.166	1.341	1.180	1.187
2 x 6	Select Structural	10	4.938	1.725	.352	1.954	1.882	2.025	1.894	1.867
		15	2.882	1.140	.899	1.902	1.822	1.983	1.835	1.799
		20	5.751	1.826	.000	1.713	1.646	1.779	1.657	1.667
		Green	5.227	1.682	.000	1.588	1.505	1.630	1.515	1.544
2 x 6	No. 2	10	3.335	1.396	.393	1.644	1.561	1.727	1.574	1.536
		15	3.701	1.593	.246	1.688	1.602	1.774	1.616	1.579
		20	3.567	1.271	.268	1.415	1.345	1.485	1.356	1.362
		Green	3.978	1.466	.000	1.337	1.266	1.409	1.277	1.271
2 x 6	No. 3	10	2.476	1.019	0.663	1.542	1.449	1.635	1.464	1.419
		15	2.355	1.146	.588	1.568	1.459	1.677	1.477	1.447
		20	2.976	1.262	.243	1.359	1.263	1.455	1.278	1.250
		Green	3.659	1.362	.043	1.275	1.182	1.368	1.197	1.135
2 x 8	Select Structural	10	3.366	1.387	.665	1.909	1.833	1.986	1.846	1.801
		15	3.861	1.334	.606	1.819	1.755	1.884	1.765	1.745
		20	5.291	1.727	.013	1.624	1.561	1.686	1.571	1.581
		Green	5.484	1.625	.000	1.520	1.464	1.575	1.473	1.467
2 x 8	No. 2	10	2.857	1.017	.695	1.590	1.514	1.666	1.526	1.535
		15	2.989	1.127	.498	1.495	1.415	1.574	1.428	1.389
		20	3.339	1.183	.273	1.334	1.259	1.408	1.271	1.245
		Green	4.248	1.298	.063	1.254	1.188	1.320	1.198	1.185
2 x 8	No. 3	10	2.399	1.404	.354	1.560	1.429	1.691	1.450	1.401
		15	2.719	1.147	.501	1.503	1.400	1.606	1.416	1.382
		20	2.407	1.014	.399	1.269	1.170	1.369	1.186	1.157
		Green	2.864	1.043	.347	1.265	1.175	1.355	1.190	1.184

[1]Table A10 indicates the degree of fit of the three-parameter Weibull distribution to the data.

Table A4.—Three-parameter Weibull distribution for the flexural stiffness of Southern Pine lumber at various moisture contents

Nominal size	Grade	Moisture content class	Estimated Weibull parameters: Shape	Scale	Location	Weibull 50 percent point: Estimate	95 percent lower confidence limit	95 percent upper confidence limit	50 percent tolerance limit, 95 percent confidence: Weibull	Nonparametric
In.		*Pct*		— — — — — —	— — — — — —	— — *10 ^{6} lb/in. ^{2}* — —	— — — — — —	— — — — — —	— — — — — —	— — — — — —
2 x 4	Select Structural	10	4.932	8.852	1.672	9.889	9.496	10.283	9.559	9.334
		15	3.769	9.158	1.405	9.715	9.221	10.208	9.300	9.132
		20	4.480	8.121	1.542	9.025	8.635	9.415	8.698	8.528
		Green	3.932	8.456	1.373	9.076	8.663	9.489	8.730	8.615
2 x 4	No. 2	10	3.750	8.020	.958	8.230	7.766	8.695	7.841	7.780
		15	3.177	8.169	1.048	8.327	7.819	8.834	7.900	7.695
		20	4.118	7.941	.000	7.265	6.866	7.663	6.930	6.919
		Green	3.947	8.364	.171	7.793	7.353	8.233	7.424	7.081
2 x 4	No. 3	10	2.832	5.927	2.388	7.596	7.148	8.044	7.220	7.175
		15	2.669	6.148	2.391	7.751	7.250	8.252	7.330	7.097
		20	2.771	5.688	2.147	7.130	6.657	7.604	6.733	6.700
		Green	2.898	6.310	1.763	7.343	6.832	7.855	6.914	6.956
2 x 6	Select Structural	10	5.607	36.545	4.717	38.949	37.609	40.290	37.824	37.295
		15	2.975	23.526	18.930	39.729	38.110	41.348	38.370	37.787
		20	6.146	40.117	.000	37.795	36.429	39.161	36.648	36.943
		Green	5.224	39.207	.000	36.551	35.092	37.009	35.327	36.013
2 x 6	No. 2	10	3.788	29.152	6.632	33.095	31.545	34.645	31.794	31.221
		15	3.808	32.712	5.442	35.153	33.446	36.860	33.721	33.264
		20	3.863	29.390	4.681	31.411	29.902	32.920	30.145	30.279
		Green	3.984	34.149	.000	31.148	29.488	32.808	29.755	29.324
2 x 6	No. 3	10	2.568	19.826	14.024	31.213	29.446	32.980	29.731	28.748
		15	2.487	24.196	12.210	33.091	30.893	35.290	31.246	30.508
		20	3.087	28.301	5.115	30.248	28.166	32.331	28.501	28.171
		Green	3.604	31.316	1.416	29.704	27.536	31.871	27.885	28.448
2 x 8	Select Structural	10	3.627	66.208	31.529	91.372	87.959	94.785	88.508	86.839
		15	4.388	69.838	26.825	91.067	88.029	94.105	88.518	88.082
		20	5.591	91.113	.000	85.332	82.211	88.454	82.713	82.797
		Green	5.507	90.294	.000	84.480	81.392	87.568	81.889	80.807
2 x 8	No. 2	10	3.006	49.369	33.556	77.259	73.724	80.795	74.292	74.943
		15	3.250	57.847	23.802	75.480	71.677	79.283	72.288	70.256
		20	3.427	62.392	14.309	70.372	66.526	74.218	67.145	65.376
		Green	4.185	71.103	4.383	69.541	65.867	73.215	66.458	65.941
2 x 8	No. 3	10	2.575	68.243	16.149	75.338	69.305	81.370	70.275	68.924
		15	2.967	59.786	23.110	75.948	70.929	80.967	71.736	70.308
		20	2.608	55.889	18.721	67.282	62.119	72.445	62.949	60.858
		Green	2.768	56.406	20.774	70.185	85.180	75.190	65.985	65.767

Table A5.—Three-parameter Weibull distribution for the moment capacity of Southern Pine lumber at various moisture contents

Nominal size	Grade	Moisture content class	Estimated Weibull parameters			Weibull 5 percent point			5 percent tolerance limit, 95 percent confidence	
			Shape	Scale	Location	Estimate	95 percent lower confi-dence limit	95 percent upper conf-dence limit	Weibull	Nonpara-metric
In.		*Pct*				*10 ^{3} lb/in. ^{2}*				
2 x 4	Select Structural	10	4.836	38.889	0.000	21.041	18.065	24.018	18.543	16.681
		15	5.025	32.538	2.270	20.286	17.900	22.671	18.284	15.238
		20	5.884	30.658	.000	18.507	16.420	20.593	16.755	15.578
		Green	3.209	19.784	8.443	16.284	14.873	17.696	15.100	14.059
2 x 4	No. 2	10	2.368	27.066	1.510	9.233	6.873	11.593	7.253	6.691
		15	3.154	27.242	.000	10.624	8.550	12.699	8.883	6.600
		20	3.619	23.769	.000	10.462	8.633	12.290	9.927	6.698
		Green	2.574	18.849	3.554	9.498	8.044	10.953	8.278	7.200
2 x 4	No. 3	10	1.824	22.262	2.947	7.316	5.858	8.775	6.092	4.773
		15	2.710	24.620	.875	9.103	6.874	11.332	7.232	6.770
		20	2.878	20.401	1.667	8.936	7.061	10.811	7.363	5.231
		Green	2.551	18.976	2.280	8.203	6.341	10.065	6.640	6.197
2 x 6	Select Structural	10	4.570	86.054	.000	44.927	39.648	50.207	40.497	30.285
		15	4.743	82.360	.000	44.028	38.767	49.288	39.613	26.055
		20	7.372	71.915	.000	48.066	44.525	51.608	45.094	33.629
		Green	5.172	65.610	.000	36.944	33.240	40.648	33.835	26.436
2 x 6	No. 2	10	1.806	51.912	8.454	18.481	15.300	21.661	15.811	13.190
		15	2.206	56.913	6.529	21.332	17.161	25.503	14.831	17.204
		20	2.159	41.243	10.999	21.420	18.754	24.087	19.182	17.464
		Green	2.123	43.058	6.803	17.432	14.435	20.429	14.917	12.420
2 x 6	No. 3	10	2.172	58.001	2.609	17.386	12.548	22.223	13.326	8.155
		15	1.770	49.494	8.648	17.892	14.166	21.618	14.765	13.147
		20	2.283	44.156	6.945	18.970	15.248	22.692	15.846	11.561
		Green	1.719	34.373	10.170	16.275	13.712	18.838	14.124	12.485
2 x 8	Select Structural	10	3.758	139.065	.000	63.092	54.076	72.108	55.526	44.046
		15	3.977	106.754	24.346	74.936	67.685	82.188	64.851	60.507
		20	4.965	106.862	.000	58.753	52.650	64.855	53.631	40.162
		Green	4.340	101.823	.000	51.361	44.857	57.865	45.902	36.424
2 x 8	No. 2	10	1.532	71.751	18.624	28.942	24.915	32.969	25.563	22.324
		15	2.004	83.776	13.491	32.523	26.017	39.029	27.063	24.881
		20	1.945	62.890	14.959	28.616	24.544	32.687	25.199	26.094
		Green	1.984	56.456	17.372	30.007	26.050	33.964	26.687	24.525
2 x 8	No. 3	10	1.430	82.480	15.525	25.864	21.180	30.548	21.933	17.717
		15	2.091	88.831	7.252	28.713	21.091	36.334	22.316	15.640
		20	2.298	74.396	8.355	28.784	21.526	36.042	22.693	18.962
		Green	1.804	60.481	19.193	30.848	26.452	35.244	27.158	21.920

Table A6.—Two-parameter Weibull distribution for the modulus of rupture of Southern Pine lumber at various moisture contents[1]

Nominal size	Grade	Moisture content class	Estimated Weibull parameters: Shape	Scale	Location	Weibull 5 percent point: Estimate	95 percent lower confidence limit	95 percent upper confidence limit	5 percent tolerance limit, 95 percent confidence: Weibull	Nonparametric
In.		*Pct*				*10[3] lb/in.[2]*				
2 x 4	Select Structural	10	4.659	13.322	0	7.042	6.199	7.885	6.334	5.127
		15	5.293	11.586	0	6.610	5.943	7.277	6.050	4.983
		20	5.853	9.721	0	5.852	5.321	6.383	5.407	4.895
		Green	4.862	8.703	0	4.725	4.258	5.192	4.333	4.267
2 x 4	No. 2	10	2.532	9.781	0	3.026	2.346	3.706	2.455	2.272
		15	3.051	8.982	0	3.393	2.807	3.979	2.901	2.139
		20	3.587	7.530	0	3.290	2.793	3.786	2.873	2.137
		Green	3.250	6.928	0	2.778	2.324	3.233	2.397	2.193
2 x 4	No. 3	10	2.253	8.806	0	2.356	1.760	2.953	1.856	1.563
		15	2.774	8.438	0	2.892	2.275	3.508	2.374	2.141
		20	3.159	7.021	0	2.742	2.209	3.274	2.295	1.611
		Green	2.993	6.536	0	2.422	3.920	2.925	2.001	1.905
2 x 6	Select Structural	10	4.466	11.696	0	6.015	5.306	6.724	5.420	4.031
		15	4.726	10.803	0	5.762	5.107	6.417	5.213	3.453
		20	7.116	9.059	0	5.967	5.522	6.413	5.593	4.169
		Green	5.204	7.920	0	4.475	4.043	4.907	4.113	3.166
2 x 6	No. 2	10	2.328	8.467	0	2.364	1.824	2.903	1.911	1.788
		15	2.585	8.470	0	3.684	2.154	3.214	2.239	2.254
		20	3.010	6.743	0	2.514	2.094	2.933	2.162	2.202
		Green	2.661	6.160	0	2.017	1.632	2.403	1.694	1.506
2 x 6	No. 3	10	2.313	8.241	0	2.282	1.668	2.895	1.767	1.079
		15	2.309	7.844	0	2.168	1.595	2.740	1.687	1.644
		20	2.803	6.517	0	2.259	1.767	2.751	1.816	1.454
		Green	2.587	5.629	0	1.786	1.347	2.225	1.416	1.500
2 x 8	Select Structural	10	3.651	10.587	0	4.693	4.051	5.335	4.154	3.206
		15	4.914	9.706	0	5.303	4.802	5.803	4.883	4.305
		20	4.879	7.556	0	4.110	3.701	4.520	3.767	2.843
		Green	4.337	6.882	0	3.469	3.092	3.846	3.153	2.493
2 x 8	No. 2	10	2.299	7.181	0	1.972	1.483	2.462	1.561	1.626
		15	2.502	7.280	0	2.222	1.707	2.736	1.789	1.824
		20	2.701	5.693	0	1.896	1.510	2.282	1.572	1.815
		Green	2.937	5.173	0	1.882	1.531	2.232	1.588	1.646
2 x 8	No. 3	10	2.001	7.864	0	1.782	1.226	2.339	1.315	1.306
		15	2.364	7.126	0	2.029	1.470	2.587	1.560	1.124
		20	2.679	5.905	0	1.949	1.481	2.417	1.556	1.325
		Green	2.744	5.634	0	1.909	1.472	2.346	1.542	1.472

[1]Table All indicates the degree of fit of the two-parameter Weibull distribution.

Table A7.—Two-parameter Weibull distribution for the modulus of elasticity of Southern Pine lumber at various moisture contents’

			Estimated Weibull parameters			Weibull 50 percent point			50 percent tolerance limit, 95 percent confidence	
Nominal size	Grade	Moisture content class	Shape	Scale	Location	Estimate	95 percent lower confidence limit	95 percent upper confidence limit	Weibull	Nonparametric
In.		*Pct*				*10* ^{6} lb/in. ^{2}				
2 x 4	Select Structural	10	5.561	2.119	0	1.984	1.902	2.065	1.915	1.825
		15	4.335	2.049	0	1.883	1.787	1.978	1.803	1.757
		20	5.291	1.758	0	1.641	1.573	1.708	1.584	1.551
		Green	4.695	1.687	0	1.561	1.493	1.628	1.504	1.470
2 x 4	No. 2	10	4.040	1.793	0	1.637	1.543	1.731	1.558	1.496
		15	3.550	1.776	0	1.602	1.504	1.700	1.519	1.439
		20	4.032	1.435	0	1.310	1.240	1.381	1.251	1.244
		Green	4.024	1.461	0	1.334	1.261	1.406	1.273	1.218
2 x 4	No. 3	10	3.939	1.668	0	1.520	1.428	1.612	1.443	1.366
		15	3.736	1.666	0	1.510	1.412	1.609	1.427	1.321
		20	4.027	1.437	0	1.312	1.229	1.396	1.242	1.197
		Green	3.963	1.403	0	1.279	1.197	1.361	1.211	1.187
2 x 6	Select Structural	10	6.083	2.086	0	1.964	1.895	2.032	1.906	1.867
		15	5.594	2.077	0	1.946	1.869	2.022	1.882	1.799
		20	5.751	1.826	0	1.713	1.648	1.777	1.659	1.667
		Green	5.227	1.682	0	1.568	1.507	1.629	1.516	1.544
2 x 6	No. 2	10	4.516	1.814	0	1.672	1.591	1.754	1.604	1.536
		15	4.407	1.850	0	1.702	1.622	1.783	1.635	1.579
		20	4.501	1.552	0	1.431	1.365	1.497	1.375	1.362
		Green	3.978	1.466	0	1.337	1.267	1.407	1.278	1.271
2 x 6	No. 3	10	4.439	1.730	0	1.593	1.500	1.686	1.515	1.419
		15	3.943	1.783	0	1.625	1.522	1.728	1.539	1.447
		20	3.749	1.525	0	1.383	1.291	1.475	1.306	1.250
		Green	3.808	1.408	0	1.278	1.191	1.366	1.205	1.135
2 x 8	Select Structural	10	5.272	2.082	0	1.942	1.867	2.016	1.879	1.801
		15	5.895	1.959	0	1.841	1.779	1.902	1.789	1.745
		20	5.336	1.740	0	1.624	1.564	1.684	1.573	1.581
		Green	5.484	1.625	0	1.520	1.466	1.573	1.475	1.467
2 x 8	No. 2	10	5.184	1.746	0	1.627	1.553	1.700	1.565	1.535
		15	4.619	1.655	0	1.528	1.450	1.606	1.463	1.389
		20	4.315	1.473	0	1.353	1.281	1.425	1.293	1.245
		Green	4.502	1.364	0	1.257	1.194	1.321	1.204	1.185
2 x 8	No. 3	10	3.277	1.800	0	1.610	1.486	1.734	1.506	1.401
		15	4.251	1.680	0	1.541	1.445	1.637	1.460	1.382
		20	3.689	1.449	0	1.312	1.219	1.405	1.234	1.157
		Green	4.095	1.413	0	1.292	1.209	1.375	1.222	1.184

[1]Table All indicates the degree of fit of the two-parameter Weibull distribution.

Table A8.—Two-parameter Weibull distribution for the flexural stiffness of Southern Pine lumber at various moisture contents

Nominal size	Grade	Moisture content class	Estimated Weibull parameters			Weibull 50 percent point			50 percent tolerance limit, 95 percent confidence	
			Shape	Scale	Location	Estimate	95 percent lower confi-dence limit	95 percent upper confi-dence limit	Weibull	Nonpara-metric
In.		*Pct*		— — — — — — — — —	— — — —	10 ^{6} lb/in. ^{2}	— — — —	— — — — — — — — —		
2 x 4	Select Structural	10	6.004	10.566	0	9.940	9.563	10.317	9.624	9.334
		15	4.505	10.639	0	9.808	9.330	10.286	9.407	9.132
		20	5.466	9.707	0	9.077	8.716	9.438	8.774	8.528
		Green	4.705	9.888	0	9.147	8.754	9.540	8.817	8.615
2 x 4	No. 2	10	4.312	9.028	0	8.293	7.847	8.738	7.919	7.780
		15	3.741	9.305	0	8.437	7.948	8.926	8.026	7.695
		20	4.118	7.941	0	7.265	6.882	7.648	6.943	6.919
		Green	4.051	8.544	0	7.805	7.384	8.226	7.452	7.081
2 x 4	No. 3	10	4.282	8.475	0	7.780	7.349	8.210	7.418	7.175
		15	4.019	8.725	0	7.965	7.482	8.448	7.560	7.097
		20	4.119	7.991	0	7.311	6.855	7.766	6.928	6.700
		Green	3.964	8.216	0	7.491	7.013	7.968	7.089	6.956
2 x 6	Select Structural	10	6.417	41.358	0	39.062	37.773	40.350	37.980	37.295
		15	5.794	43.209	0	40.560	39.029	42.092	39.275	37.787
		20	6.146	40.117	0	37.795	36.463	39.127	36.677	36.943
		Green	5.224	39.207	0	36.551	35.127	37.975	35.356	36.013
2 x 6	No. 2	10	4.851	36.116	0	33.488	31.973	35.003	32.217	31.221
		15	4.584	38.400	0	35.449	33.832	37.066	34.092	33.264
		20	4.616	34.276	0	31.660	30.231	33.089	30.461	30.279
		Green	3.984	34.149	0	31.148	29.519	32.777	29.781	29.324
2 x 6	No. 3	10	4.771	34.716	0	32.149	30.409	33.889	30.689	28.748
		15	4.111	37.330	0	34.145	32.078	36.213	32.410	30.508
		20	3.831	33.815	0	30.730	28.730	32.731	29.051	28.171
		Green	3.814	32.819	0	29.812	27.771	31.852	28.099	26.448
2 x 8	Select Structural	10	5.640	98.888	0	92.666	89.344	95.989	89.878	86.839
		15	6.309	97.328	0	91.835	88.973	94.698	89.433	88.082
		20	5.591	91.113	0	85.332	82.306	88.359	82.792	82.797
		Green	5.507	90.294	0	84.480	81.506	87.454	81.984	80.807
2 x 8	No. 2	10	5.422	84.392	0	78.876	77.473	82.279	76.020	74.943
		15	4.876	82.869	0	76.868	73.153	80.583	73.751	70.256
		20	4.413	77.505	0	71.327	67.625	75.029	68.221	65.376
		Green	4.504	75.699	0	69.782	67.267	73.298	66.832	65.941
2 x 8	No. 3	10	3.432	86.005	0	77.295	71.617	82.973	72.530	68.924
		15	4.418	84.190	0	77.486	72.848	82.125	73.594	70.308
		20	3.772	76.124	0	69.076	64.296	73.856	65.064	60.858
		Green	4.090	78.574	0	71.839	67.224	76.454	67.966	65.767

Table A9.—Two-parameter Weibull distribution for the moment capacity of Southern Pine lumber at various moisture contents

			Estimated Weibull parameters			Weibull 5 percent point			5 percent tolerance limit, 95 percent confidence	
Nominal size	Grade	Moisture content class	Shape	Scale	Location	Estimate	95 percent lower confidence limit	95 percent upper confidence limit	Weibull	Nonparametric
In.		*Pct*					10^3 *lb/in.*^{2}			
2 x 4	Select Structural	10	4.836	38.889	0	21.041	18.615	23.467	19.005	16.681
		15	5.427	34.865	0	20.170	18.192	22.148	18.510	15.238
		20	5.884	30.658	0	18.507	16.846	20.167	17.113	15.578
		Green	4.870	28.620	0	15.553	14.024	17.083	14.270	14.059
2 x 4	No. 2	10	2.572	28.792	0	9.073	7.061	11.085	7.385	6.691
		15	3.154	27.242	0	10.624	8.845	12.403	9.131	6.600
		20	3.619	23.769	0	10.462	8.897	12.026	9.149	6.698
		Green	3.259	22.756	0	9.146	7.655	10.638	7.895	7.200
2 x 4	No. 3	10	2.301	26.043	0	7.163	5.382	8.945	5.668	4.773
		15	2.850	25.592	0	9.026	7.147	10.905	7.449	6.770
		20	3.206	22.222	0	8.800	7.107	10.492	7.379	5.231
		Green	2.989	21.494	0	7.956	6.304	9.608	6.569	6.197
2 x 6	Select Structural	10	4.570	86.054	0	44.927	39.742	50.113	40.576	30.285
		15	4.743	82.360	0	44.028	39.063	48.992	39.861	26.055
		20	7.372	71.915	0	48.066	44.590	51.543	45.159	33.629
		Green	5.172	65.610	0	36.944	33.357	40.531	33.934	26.436
2 x 6	No. 2	10	2.357	62.517	0	17.728	13.724	21.733	14.368	13.190
		15	2.606	64.461	0	20.625	6.588	24.663	17.237	17.204
		20	3.031	53.731	0	20.169	16.819	23.519	17.357	17.464
		Green	2.662	50.980	0	16.706	13.516	19.895	14.028	12.420
2 x 6	No. 3	10	2.349	61.174	0	17.279	12.678	21.880	13.417	8.155
		15	2.330	60.122	0	16.805	12.394	21.216	13.104	13.147
		20	2.837	52.048	0	18.266	14.332	22.201	14.964	11.561
		Green	2.590	46.612	0	14.810	11.180	18.440	11.763	12.485
2 x 8	Select Structural	10	3.758	139.065	0	63.092	54.686	71.498	56.038	44.046
		15	5.047	131.984	0	73.273	66.515	80.031	67.601	60.507
		20	4.965	106.862	0	58.753	52.999	64.507	53.924	40.162
		Green	4.340	101.823	0	51.361	45.781	56.942	46.678	36.424
2 x 8	No. 2	10	2.306	95.822	0	26.424	19.896	32.953	20.945	22.324
		15	2.537	99.598	0	30.893	23.816	37.970	24.954	24.881
		20	2.721	80.799	0	27.124	21.651	32.596	22.531	26.094
		Green	2.930	76.479	0	27.753	22.573	32.932	23.406	24.525
2 x 8	No. 3	10	2.033	103.744	0	24.064	16.647	31.480	17.839	17.717
		15	2.390	97.532	0	28.145	20.483	35.806	21.715	15.640
		20	2.691	83.858	0	27.813	21.153	34.473	22.224	18.962
		Green	2.747	83.382	0	28.278	21.804	34.753	22.845	21.920

Table A10.--Evaluation of the fit of a three-parameter Weibull distribution to the modulus of rupture and modulus of elasticity data

			Indicators of fit for modulus of rupture			Indicators of fit for modulus of elasticity		
				Percent difference in property estimate[2]			Percent difference in property estimate*	
Moisture content group	Nominal size	Grade	Lack of fit[1]	Median	Fifth percentile	Lack of fit[1]	Median	Fifth percentile
Pct	*In.*							
Green	2 x 4	Select Structural	—	-0.2	3.1	—	0.5	3.2
		No. 2	—	-1.8	7.9	—	0.5	0.9
		No. 3	—	-2.0	8.6	—	-0.9	4.1
	2 x 6	Select Structural	—	1.4	19.2	—	1.2	7.6
		No. 2	—	-3.7	13.0	—	0.4	-3.1
		No. 3	*	-7.1	4.5	—	0.3	3.3
	2 x 8	Select; Structural	—	1.0	14.3	—	1.4	3.5
		No. 2	—	-4.5	8.1	—	0.7	3.8
		No. 3	—	-6.0	3.2	—	-0.8	-5.4
20	2 x 4	Select Structural	—	1.6	8.1	—	0.8	3.7
		No. 2	*	0.4	11.4	—	0.7	10.6
		No. 3	—	-1.3	4.4	—	-1.4	2.4
	2 x 6	Select Structural	—	1.6	-1.4	—	1.4	9.8
		No. 2	—	-3.6	-5.6	—	0.1	-2.7
		No. 3	—	-3.5	0.2	—	-0.8	-4.1
	2 x 8	Select Structural	*	1.3	18.3	—	-1.6	-3.2
		No. 2	—	-5.5	0.6	—	0.0	4.3
		No. 3	*	-3.5	4.5	—	-2.2	8.4
15	2 x 4	Select Structural	—	1.4	-2.8	—	0.3	-3.9
		No. 2	—	-0.7	8.9	—	-1.1	-6.8
		No. 3	—	-2.4	11.6	—	-2.2	4.1
	2 x 6	Select Structural	—	1.3	5.8	—	-0.7	4.6
		No. 2	*	-4.0	13.2	—	0.3	2.8
		No. 3	*	-7.6	15.6	—	-2.2	7.3
	2 x 8	Select Structural	—	0.3	4.9	—	0.3	1.2
		No. 2	*	-5.8	9.1	—	-0.7	-4.6
		No. 3	*	-5.0	18.7	—	-1.1	0.5
10	2 x 4	Select Structural	—	1.3	0.6	—	0.6	-5.1
		No. 2	—	-3.6	20.9	—	-0.4	-5.1
		No. 3	—	-7.9	-4.9	—	-1.9	-1.6
	2 x 6	Select Structural	—	1.2	9.5	—	0.9	4.9
		No. 2	—	-7.6	-2.3	—	-0.4	-10.6
		No. 3	—	-5.0	10.1	—	-1.7	-5.6
	2 x 8	Select Structural	—	0.5	18.1	—	-0.2	-2.1
		No. 2	*	-9.8	2.9	—	-0.7	4.0
		No. 3	*	-13.4	14.7	—	-2.4	-4.6

[1]* (**) Indicate significant lack of fit at the p = 0.05 (01) level using the Anderson-Darling test (1954) and Stephens (1977).--Indicates test not significant at the p = 0.05 level.

[2]Percent difference = 100 (Weibull estimate - nonparametric estimate) ÷ nonparametric estimate.

Table A11.--Evaluation of the fit of a two-parameter Weibull distribution to the modulus of rupture and modulus of elasticity data

Moisture content group	Nominal size	Grade	Indicators of fit for modulus of rupture			Indicators of fit for modulus of elasticity		
			Lack of fit[1]	Percent difference in property estimate[2]		Lack of fit[1]	Percent difference in property estimate[2]	
				Median	Fifth percentile		Median	Fifth percentile
Pct	*In.*							
Green	2 x 4	Select Structural	—	1.5	-1.3	—	1.2	1.4
		No. 2	—	-6.3	-9.4	—	-3.4	-4.5
		No. 3	—	6.5	20.9	—	5.5	5.0
	2 x 6	Select Structural	—	1.4	19.2	—	1.2	7.6
		No. 2	—	-1.2	8.4	—	0.4	-3.1
		No. 3	—	-1.1	-4.6	—	0.6	2.9
	2 x 8	Select Structural	—	1.0	14.3	—	1.4	3.5
		No. 2	—	0.1	0.2	—	1.0	3.4
		No. 3	*	0.0	-0.2	—	1.3	-9.8
20	2 x 4	Select Structural	—	1.6	8.1	—	1.5	1.8
		No. 2	**	0.4	11.4	—	0.7	10.6
		No. 3	—	-0.1	2.5	*	1.3	-3.2
	2 x 6	Select Structural	—	1.6	-1.4	—	1.4	9.8
		No. 2	**	0.3	-11.1	—	1.3	-5.0
		No. 3	—	-0.7	-3.9	—	0.9	-6.4
	2 x 8	Select Structural	*	1.3	18.3	—	-1.6	-2.1
		No. 2	*	-0.2	-5.2	—	1.2	1.6
		No. 3	**	-1.3	0.5	—	1.1	1.3
15	2 x 4	Select Structural	—	1.5	-3.2	—	1.2	-4.9
		No. 2	—	-0.7	8.9	**	0.8	-8.2
		No. 3	—	-1.2	9.7	*	1.3	-3.3
	2 x 6	Select Structural	—	1.3	5.8	—	-1.6	-2.2
		No. 2	—	-1.7	9.5	—	1.1	1.0
		No. 3	*	-2.9	8.8	—	-1.4	-1.3
	2 x 8	Select Structural	—	1.3	2.1	—	1.5	-2.1
		No. 2	**	-1.9	3.2	*	1.5	-9.3
		No. 3	*	-2.7	16.3	—	1.4	-5.3
10	2 x 4	Select Structural	—	1.3	0.6	—	1.4	-6.9
		No. 2	—	-2.2	18.1	—	1.0	-7.1
		No. 3	**	-2.4	-7.1	—	1.5	-8.5
	2 x 6	Select Structural	—	1.1	9.5	—	-1.4	3.5
		No. 2	*	-2.1	-6.8	**	1.3	-13.0
		No. 3	—	-3.1	9.4	*	1.0	-13.8
	2 x 8	Select Structural	—	0.5	18.1	*	1.5	-6.4
		No. 2	**	-2.2	-5.5	—	1.6	-2.9
		No. 3	**	-4.8	6.9	—	0.7	-8.9

[1]* (**) Indicate significant lack of fit at the p = 0.05 (0.01) level using the Anderson-Darling test (1954) and Stephens (1977).--Indicates test not significant at the p = 0.05 level.

[2]Percent difference = 100 (Weibull estimate - nonparametric estimate) ÷ nonparametric estimate.

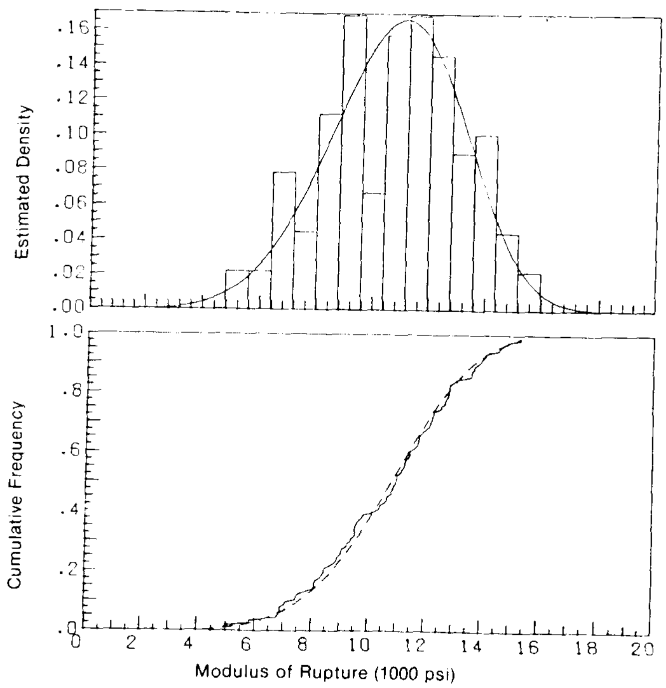


Figure A1.—Typical fit of three-parameter Weibull distribution to MOR data (2 by 4, Select Structural, 15 pct moisture content). (ML84 5322)

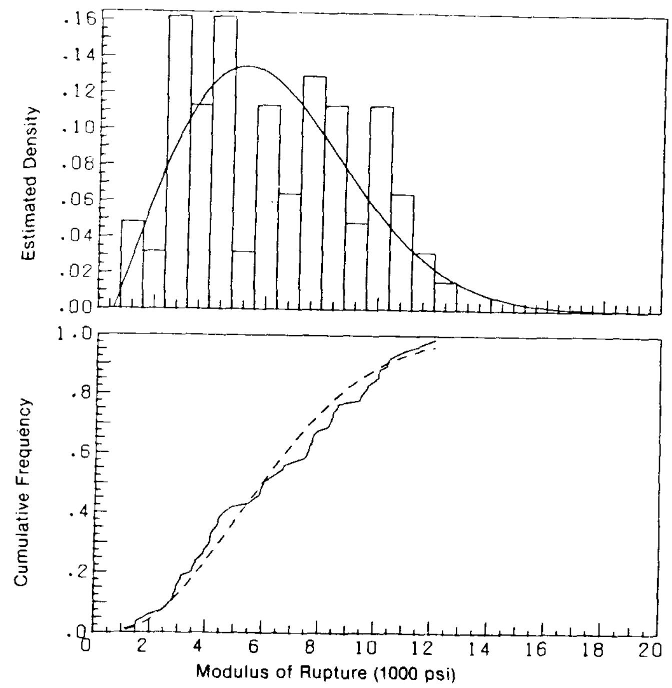


Figure **A3.—Fit** *of three-parameter Weibull distribution to biomodal data (2 by 8, No. 3, 15 pct moisture content). (ML84 5324)*

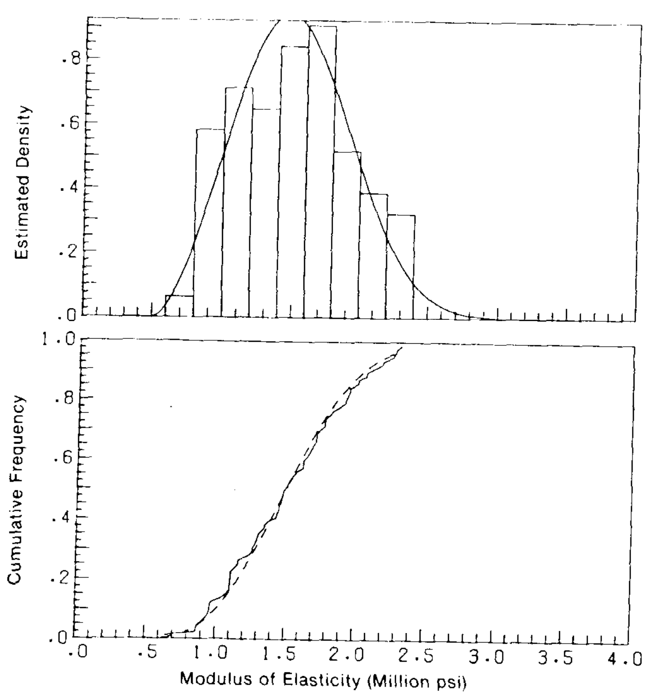


Figure A2.—Typical fit of three-parameter Weibull distribution to MOE data (2 by 8, No. 3, 15 pct moisture content). (ML84 5323)

Appendix B
Supplemental Figures

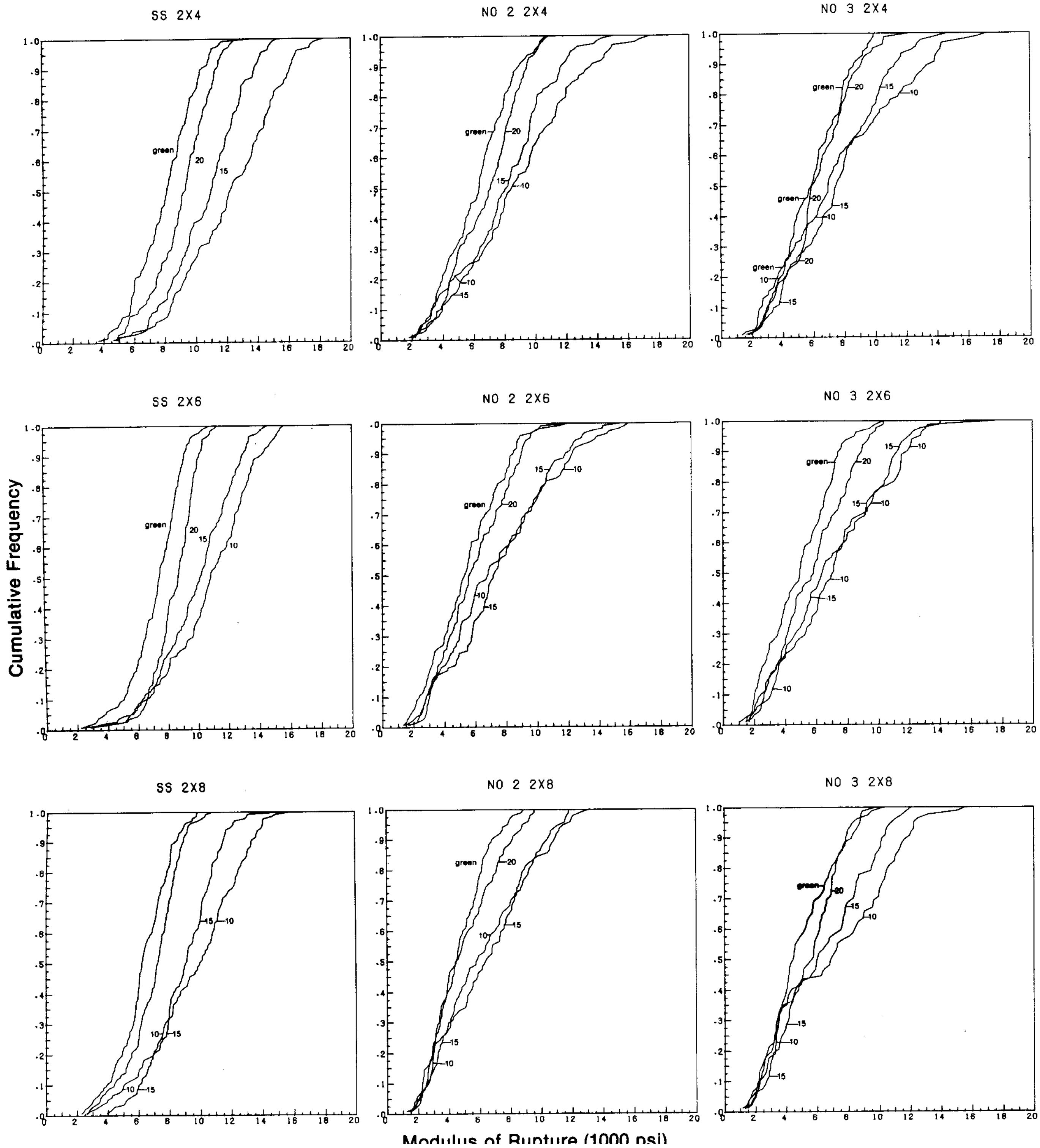


Figure B1.—Cumulative frequency distributions for MOR **at** *the four moisture content levels. (ML84 5268)*

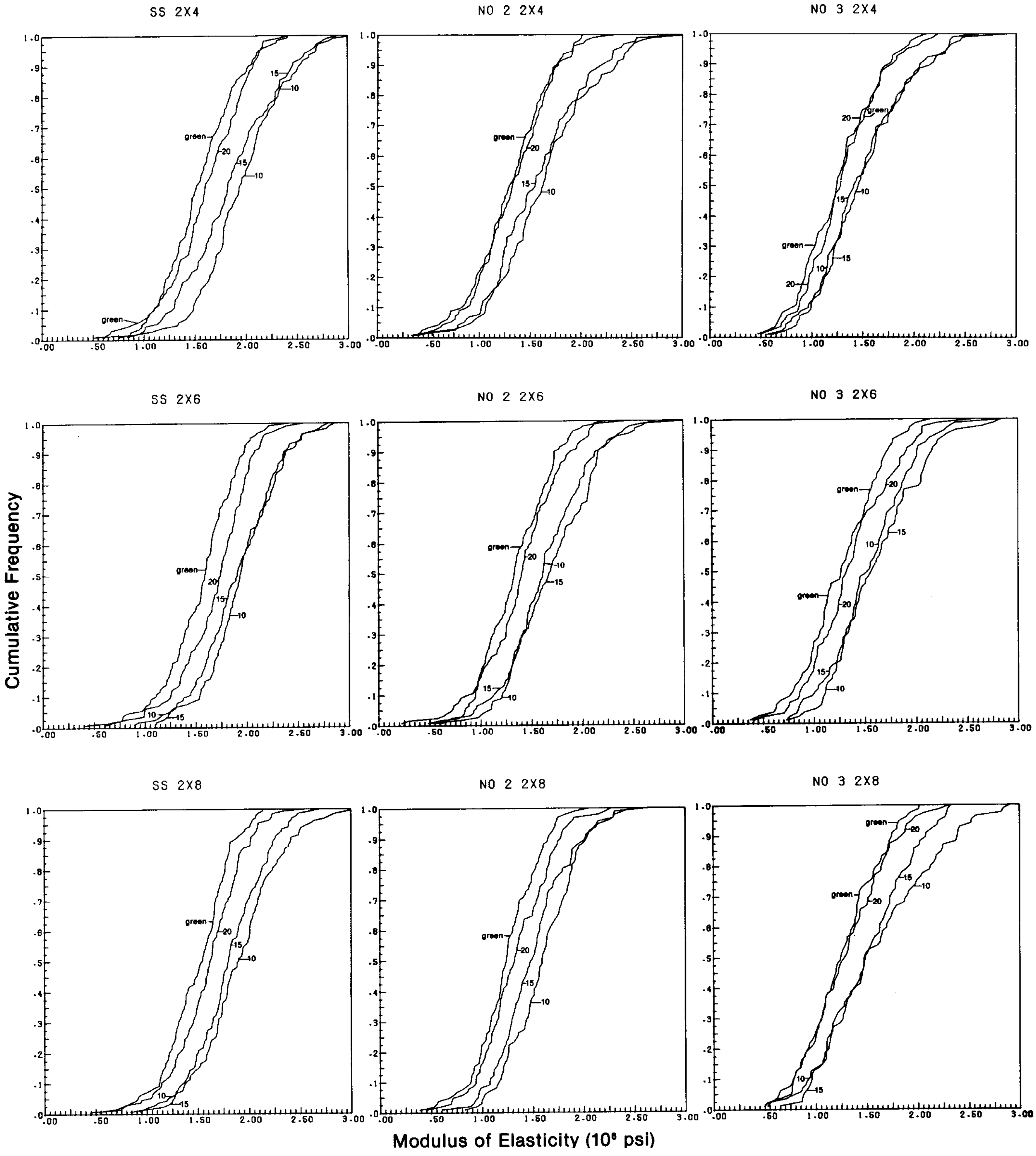


Figure B2.—Cumulative frequency distributions for MOE at the four moisture content levels. (ML84 5267)

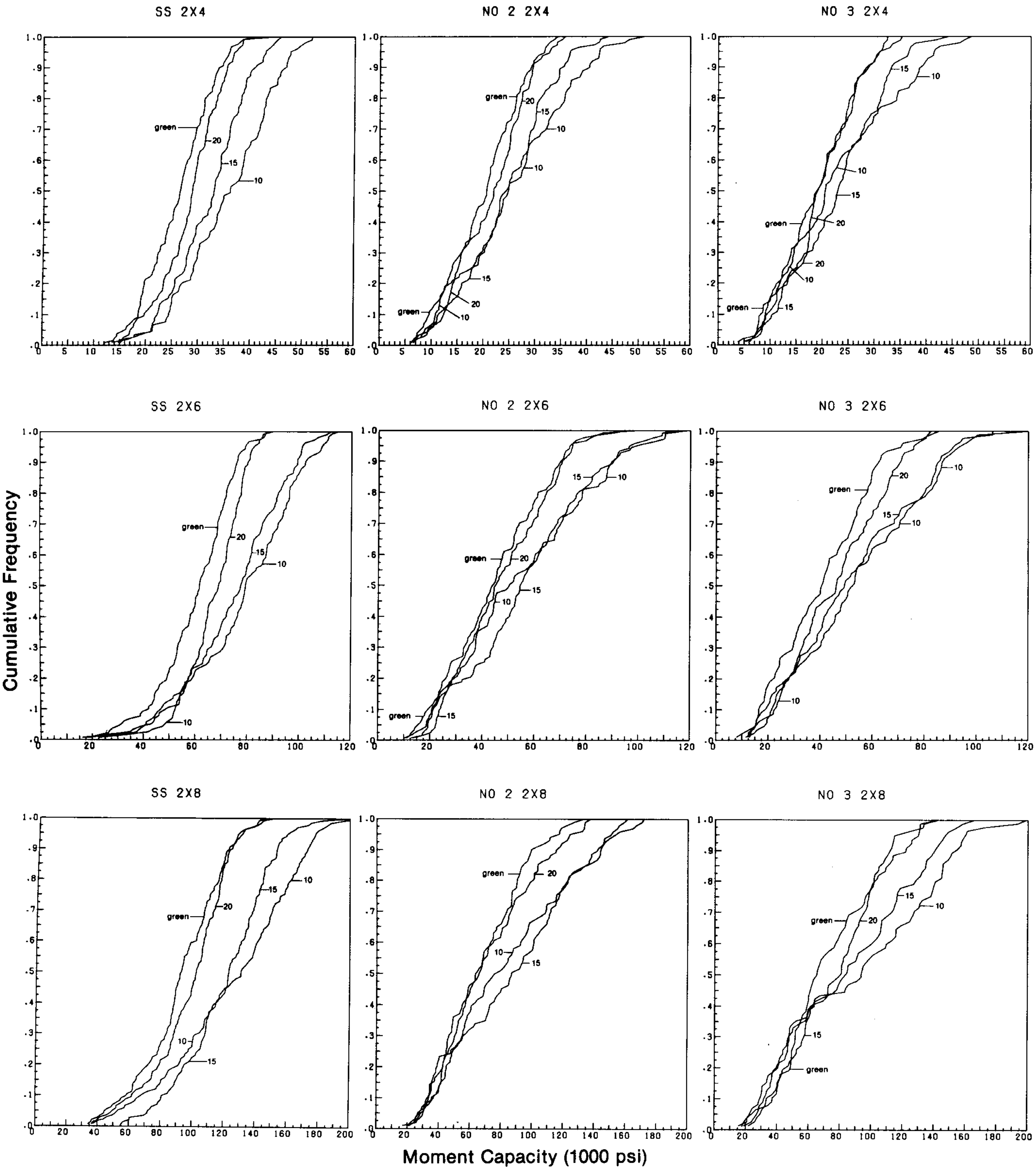


Figure B3.—Cumulative frequency distribution for RS at four moisture content levels. (ML84 5266)

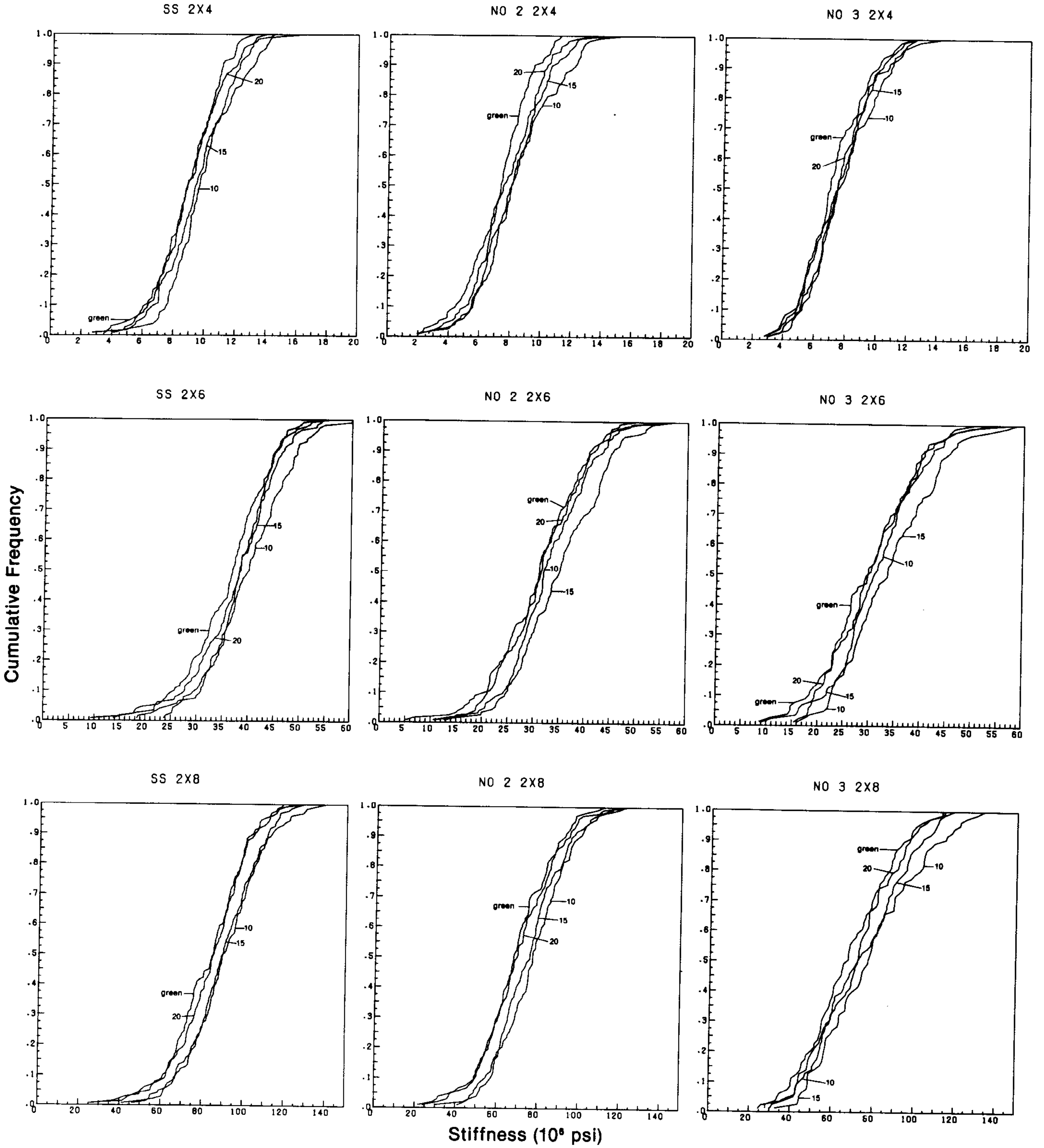


Figure B4.—Cumulative frequency distribution for EI at four moisture content levels. (ML84 5263)

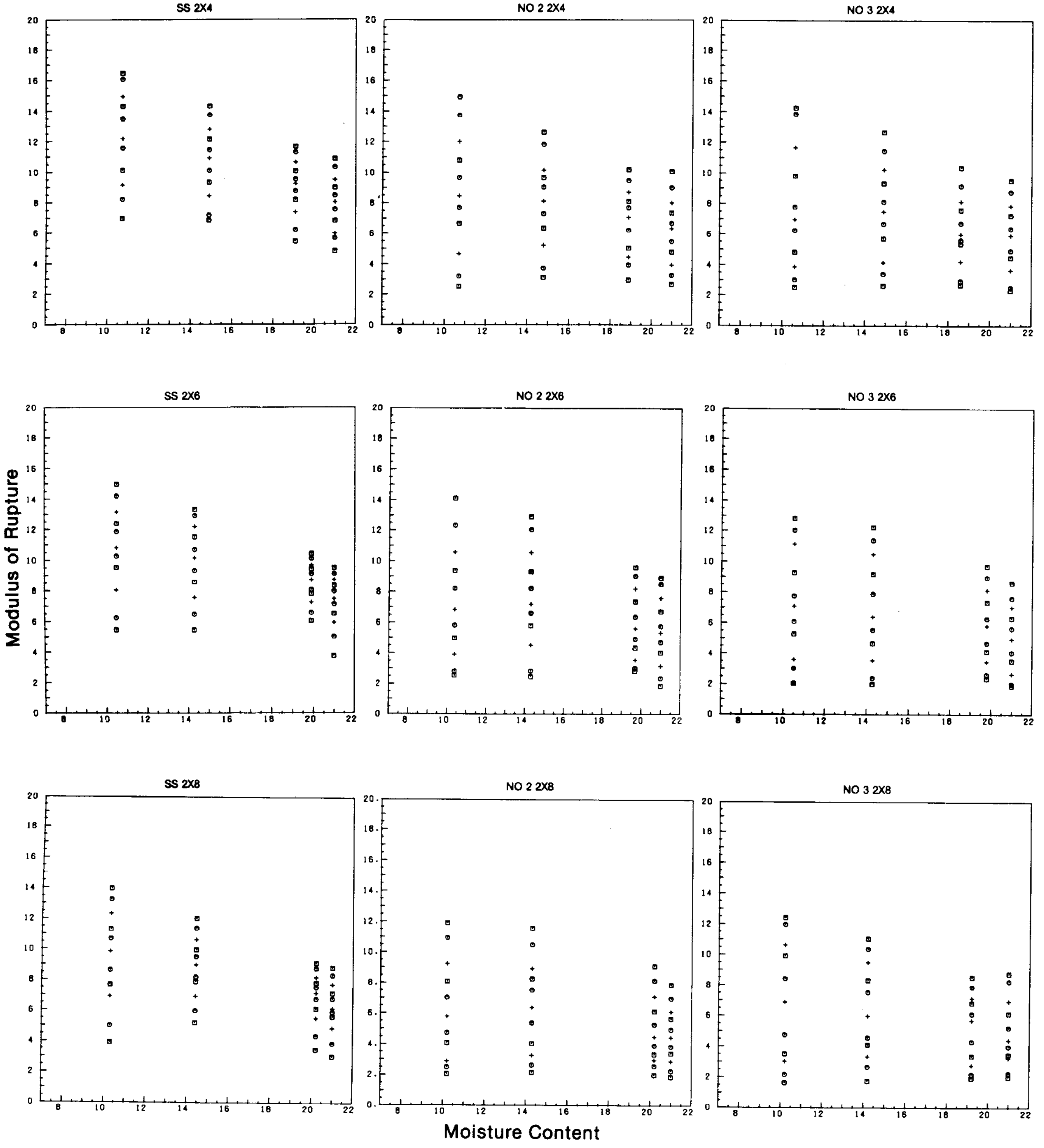


Figure B5.—Effect of moisture content on modulus of rupture (10^3 psi) at various percentile levels (5, 10, 20...80, 90, 95). Percentiles plotted at average moisture content for the groups. (21 pct for green). (ML84 5270)

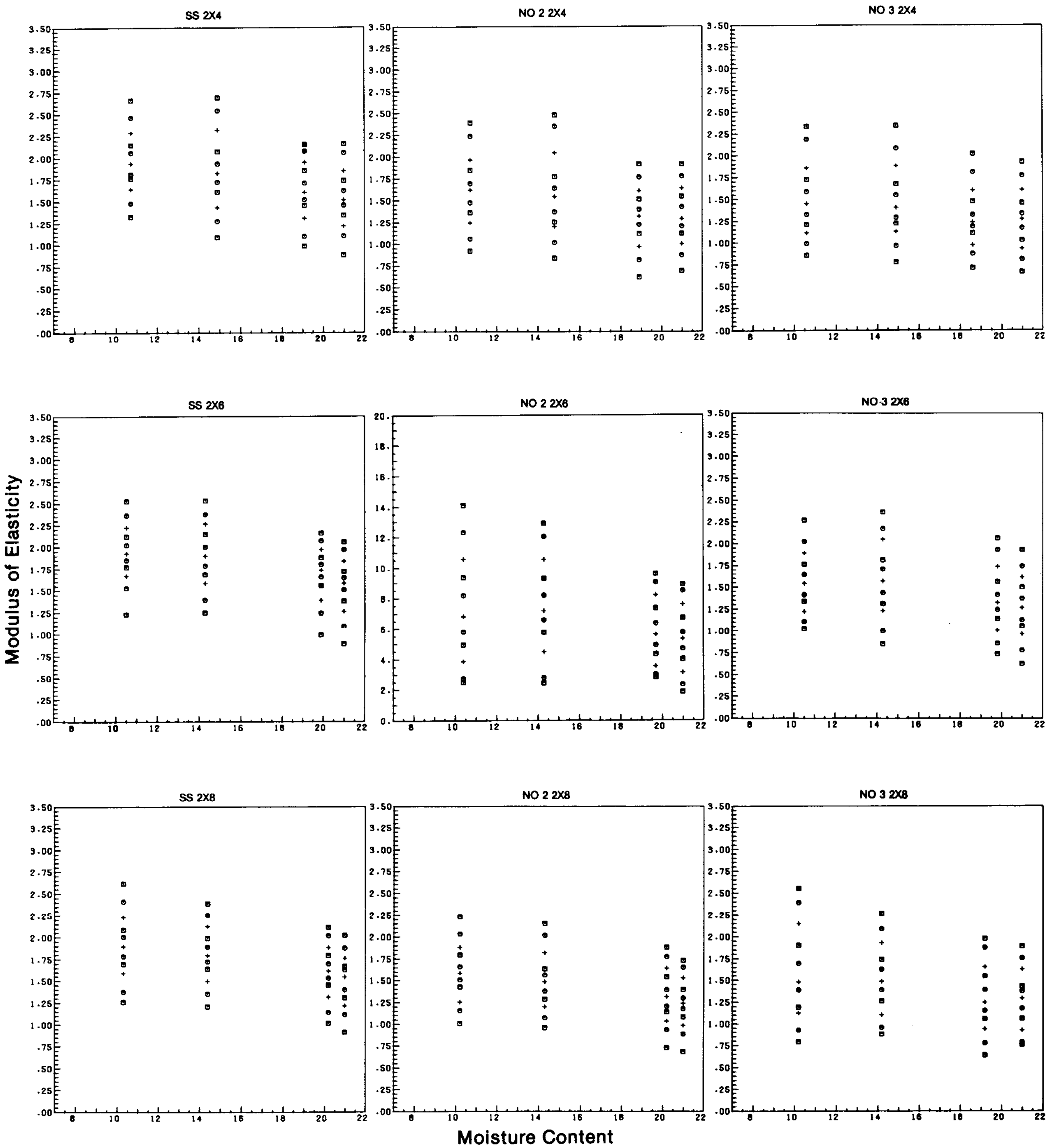


Figure B6.—Effect of moisture content on modulus of elasticity (10^6 psi) at various percentile levels (5, 10, 20...80, 90, 95). Percentiles plotted at average moisture content for the group (21 pct for green). (ML84 5264)

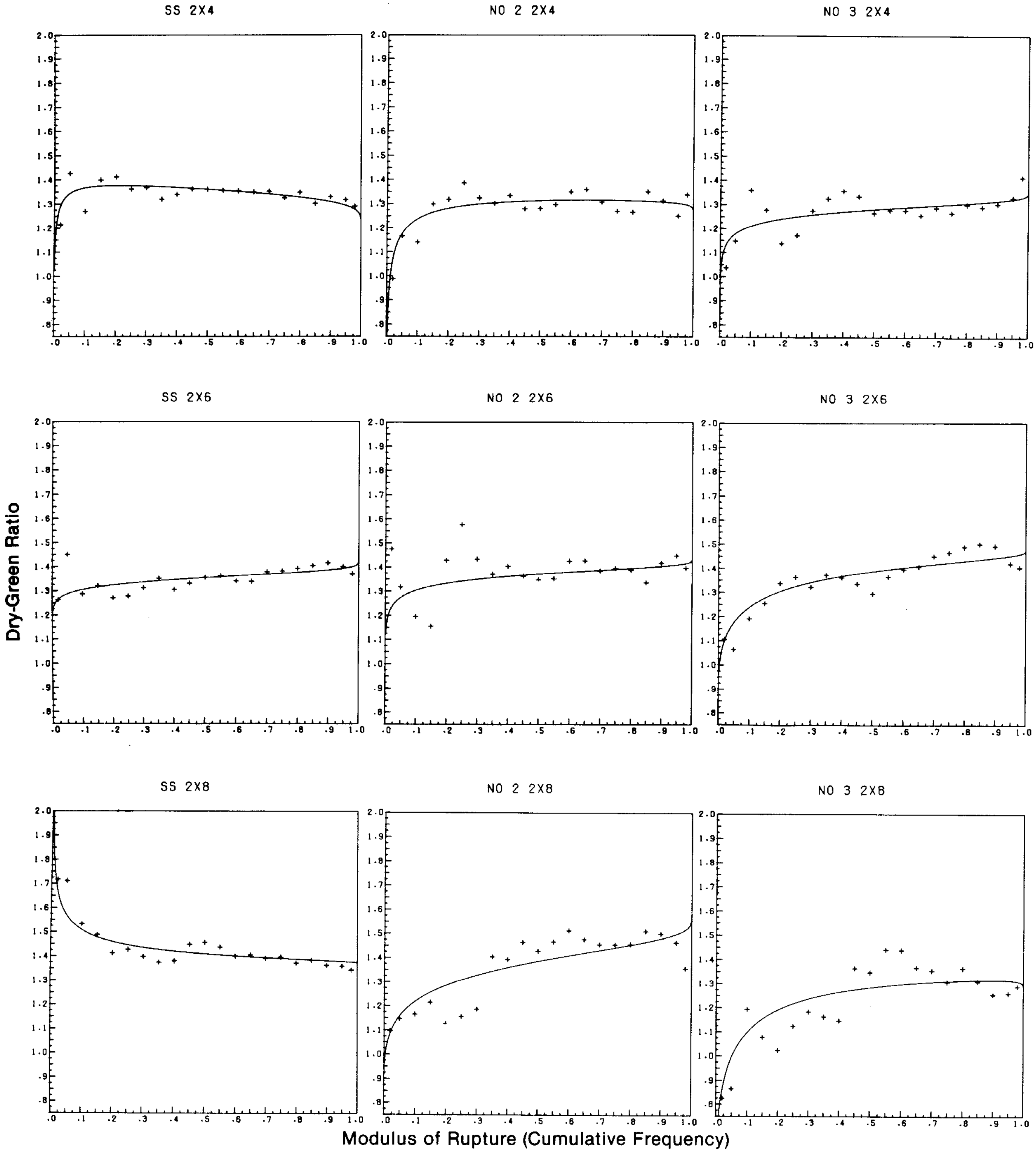


Figure B7.—Effect of percentile level on the modulus of rupture dry-green ratio for lumber dried to a moisture content of 15 percent ("+" = experimental ratio at 2, 5, 10, 15... 90, 95, 98 percentiles; solid line = ratio obtained by first fitting three-parameter Weibull distributions to the MOR values (10^3 psi) for 15 percent and green moisture contents). (ML84 5285)

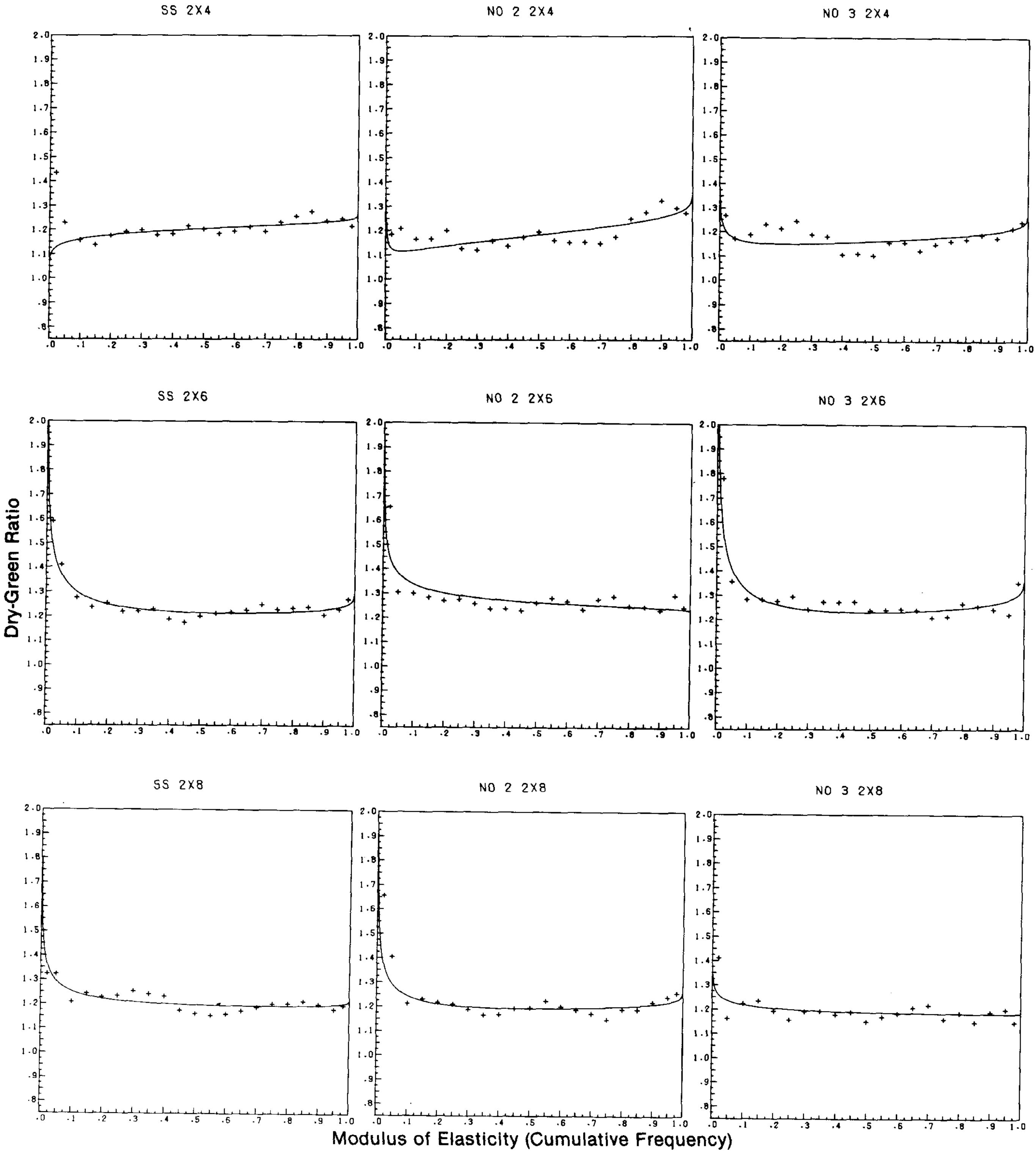


Figure B8.—Effect of percentile level on the modulus of elasticity dry-green ratio for lumber dried to a moisture content of 15 percent ("+" = experimental ratio at 2, 5, 10, 15... 90, 95, 98 percentiles; solid line = ratio obtained by first fitting three-parameter Weibull distributions to the MOE values (10^6 psi) for 15 percent and green moisture contents). (ML84 5269)

2.0-11/84

☆ U S GOVERNMENT PRINTING OFFICE 1984—754-040-10016