EFFECT OF MOISTURE CONTENT ON STRENGTH OF CCA-TREATED LUMBER

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ABSTRACT

Recent studies on the effects of chromated copper arsenate (CCA) treatment on lumber design properties have primarily evaluated the effects of such treatment at or near 12% moisture content and at failure times of 1 to 10 min. The influence of various moisture contents and faster loading rates is unknown. This report discusses the influence of moisture content and its interaction with time-to-failure on the bending strength of CCA-treated (0.4 lb/ft³ (6.4 kg/m³)) lumber. The factors studied were moisture contents of 10, 15, and ≥23% (green lumber) and ramp-load failure times in bending of 3–6, 30–60, and 300–600 seconds. This research concluded that a revised wet-use service factor for No. 1 and better waterborne-preservative-treated lumber is needed.

Keywords: CCA, preservative, treatment, mechanical properties, moisture content, duration-of-load.

PROBLEM

Recent studies on the effects of waterborne-preservative treatment on lumber design stresses have evaluated the effects of such treatment at near static loading conditions (time-to-failure of 30–300 sec) and at a 12% equilibrium moisture content (MC) (Winandy 1991). Winandy (1991) concluded that post-treatment redrying and lumber quality (i.e., grade) were critical in determining the effects of chromated copper arsenate (CCA) preservative treatment on lumber. Waterborne-preservative-treated lumber has been shown to have similar long-term duration of load characteristics as untreated lumber (Soltis and Winandy 1989). However, CCA-treated lumber has not been tested at rates faster than the static loading rate or at MC levels other than 12–15%. Therefore, our understanding of how short-term load durations and MC influence the allowable design properties of preservative-treated lumber is limited. Currently, the design adjustment factors for load duration and in-service MC for treated wood are the same as those for untreated wood.

The lack of a treated load-duration model is significant because CCA treatment affects dynamic properties, such as impact bending and work-to-maximum load, more than static properties. As a result, the National Design Specification (AFPA 1991) does not allow the application of the traditional load-duration modification factor for impact-loading to CCA material treated to 2.5 lb/ft³ (40.0 kg/m³). During the development of the most recent National Design Specification (AFPA 1991), the consensus was that specific engineering design guidance was needed to address whether the traditional load-duration factor for untreated wood could be applied to wood treated to terrestrial CCA retention levels (≤2.5 lb/ft³ (≤40.0 kg/m³)) under dynamic and impact load situations. For untreated lumber, these load-duration adjustment factors are currently 1.6 for wind and earthquake and 2.0 for impact loads. Recent work has shown that the load-

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TABLE 1. *Experimental design.*

Moisture content at test (percent)	Number of specimens in each experimental group					
	Untreated[a]			CCA-treated[b]		
	300–600 sec	30–60 sec	3–6 sec	300–600 sec	30–60 sec	3–6 sec
10	111	111	110	111	111	112
15	109	111	37[c]	112	111	33[c]
Green[d]	111	111	110	112	111	111

[a] The control specimens designated for testing green were treated with water at a pressure less than 75 lb/in.^{2} (0.5 MPa) and broken immediately after treatment.

[b] CCA-C treated to 0.4 lb/ft^3 (6.4 kg/m^3). Specimens designated for test at 10-/and 15-% equilibrium MC were kiln-dried after treatment at 150 F (66 C), and those designated to be tested green were broken immediately after treatment.

[c] Approximately 75 specimens per group were eliminated from the design because they were inadvertently equilibrated and tested at 10% MC conditions.

[d] Assumed to be 23% (Green et al. 1986).

duration factor for CCA-treated material in dynamic or impact load situations may need modification (Winandy 1993a). A solution to this problem was recently reported (Winandy 1994).

The lack of a treated wood MC-adjustment model is significant because preservative-treated materials are (by design) used in high-moisture environments. Because modification factors for untreated wood may not accurately reflect the performance of CCA-treated structures that are exposed to elevated MC levels and high dynamic loads, the design community is in an uninformed position.

The study reported here examines the influence of MC and its interaction with loading rate on the bending strength distributions of waterborne-preservative-treated No. 1 and better southern pine nominal 2- by 4-in. (standard 38- by 89-mm) lumber. The results are used to develop revised wet-use service factor (C_M) adjustments for CCA-treated lumber.

METHODS

The test material was 8-ft (2.3-m) long southern pine nominal 2- by 4-in. (standard 38- by 89-mm) lumber (2 by 4s). The lumber was kiln-dried by the lumber producer to 15% (19% maximum) MC using a kiln schedule not exceeding 200 F (93 C). The lumber was then inspected by a Southern Pine Inspection Bureau (SPIB) quality supervisor to be No. 1 and better material with the further requirement that the grade-limiting defect was not to be located within 20 in. (508 mm) from either end. This assured that the grade-limiting defect could then be placed in the maximum moment zone during subsequent bending tests. The decision to use higher-grade material and to center the grade-limiting defect in the maximum moment zone was considered conservative because previous studies on static strength distributions have consistently shown that higher-grade lumber is affected by CCA treatments to a greater degree than are lower grades (Winandy 1991).

The specimens were equilibrated to constant weight at 74 F (23 C) and 65% relative humidity. Each specimen was evaluated full-span (8 ft (2.44 m)) using a Metrigard E-computer to nondestructively measure transverse vibrational stiffness (EI). Because EI is highly correlated with strength, each specimen was then assigned to one of 18 experimental groups (Table 1) in a manner that assured equal EI-profiles within each of the 18 groups. As a result, this sorting procedure significantly increased the likelihood of starting with nearly equal pre-experimental strength distributions between the 18 experimental groups.

The experimental design was a 3 by 3 by 2 factorial. The factors were three times-to-failure, three MC levels at test, and two levels of treatment (untreated and CCA-treated). The design had 110 specimens per treatment-time-MC combination (Table 1). The lumber designated for preservative treatment was commercially treated using a modified full-cell process with 2.8% solution of CCA-Type C to a retention of 0.4 lb/ft^3 (6.4 kg/m^3) (AWPA 1991). The untreated material designated for testing green was water-treated to refusal. The treated lumber designated for testing at either 10 or 15% MC was kiln-dried after treatment at 150 F (66 C) with a 15 F (8 C) web-bulb depression for the first 24 h, followed by a 30 F (17 C) wet-bulb depression for the final 14 h to a target MC of 22%. The treated and untreated material designated for testing at 10% MC was equilibrated to constant weight at 73

F (23 C) and 50% relative humidity (RH). The treated and untreated material designated for testing at 15% MC was equilibrated at 80 F (27 C) and 80% RH.

Edgewise third-point bending tests were performed according to ASTM D 198 (ASTM 1991a) except that rate-of-loading was varied at rates of 0.19, 1.90, or 19.0 in./min (4.8, 48.0, or 480 mm/min) of constant-displacement head travel that produced failure times of 300–600, 30–60, or 3–6 sec, respectively. Test span was 60 in. (1,524 mm), with 20 in. (508 mm) between loading points. The span-to-depth ratio was 17:1. The grade-limiting knot was placed in the maximum-moment area of the beam and randomly placed with respect to the tensile edge. Load and center-point deflection data were collected digitally via an interfaced data-logger and a microcomputer. The modulus of elasticity (MOE) and modulus of rupture (MOR) of each specimen were calculated from these data (ASTM 1991a). The percentile values for MOE and MOR for each set of 18 groups were then nonparametrically estimated using a rank-order procedure.

To determine chemical retention, a small wafer was cut from approximately 10% of the treated specimens after mechanical testing. Analytical specimens were specifically selected after mechanical testing to represent the entire range of the bending strength distribution of each CCA-treated group. Ten specimens representing the 5th, 10th, 25th, 48th, 49th, 50th, 51st, 75th, 90th, and 95th percentiles of each group's bending strength distribution were selected from the nine treated groups. Each specimen was ground to 30 mesh (595 μm) in a Wiley[2] mill and compacted in a hydraulic press at $\geq$20,000 lb/in.^{2} ($\geq$138 MPa) to form a thin wafer. These 90 wafers were analyzed by X-ray fluorescence spectrophotometry using an ASOMA Model No. 200 spectrophotometer.

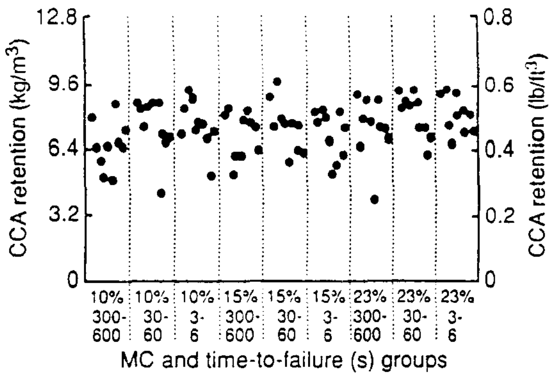

FIG. 1. Average CCA retention of nine groups of 10 wafers (90 wafers total) determined by X-ray fluorescence. Each group is ranked from lowest to highest strength, left to right, and separated by dotted vertical lines.

A subset of 12 specimens, randomly selected from the 90 assayed wafers, was analyzed using a wet-ashing technique and atomic absorption spectrometry. The atomic absorption results were used to verify the accuracy of the X-ray fluorescence results.

RESULTS AND DISCUSSION

Chemical analysis

The average CCA retention of 90 wafers determined by X-ray fluorescence was 0.459 lb/ft^3 (7.3 kg/m^3) with a standard deviation of 0.090 lb/ft^3 (1.4 kg/m^3). Only 2 of 90 CCA retention values fell below the 95% confidence lower limit using the t-statistic ($\bar{x} \pm t(s)$). The 10 observations for each of the nine groups, separated by vertical dotted lines, were ranked from the representative 5th percentile bending strength value to the corresponding 95th percentile value (Fig. 1). Based on the random nature of CCA retention within each percentile-ranked group, retention appeared to be independent of rank order within the bending strength distribution.

Comparison of the X-ray fluorescence analysis to the more precise and definitive wet ash/atomic absorption analysis indicated that the X-ray fluorescence technique was only partially reproducible. Both analytical techniques estimated nearly equal levels of copper, but

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X-ray fluorescence estimated chromium and arsenic retention levels about 11% higher than did the more time-consuming, atomic absorption spectrometry.

Effects of MC on MOE

Summary statistics for the MOE of each group are given in Table 2. As the lumber dried from green to 15% MC, the MOE uniformly increased at all three tested failure times for both untreated (Fig. 2) and CCA-treated material (Fig. 3). As the lumber dried to 10% MC, however, the influence of MC on MOE was no longer uniform across the MOE distribution. The significant ($\alpha \leq 0.05$) Treatment*MC interaction can be seen by comparing the trends in MOE in Fig. 2c to Fig. 3c. The significant ($\alpha \leq 0.05$) Time*MC can be seen by comparing the trends in MOE between Fig. 2a and Fig. 2b to Fig. 2c and between Fig. 3a and 3b to Fig. 3c. Because of these significant interactions, the effects of changing MC on MOE cannot be discussed independently from time-to-failure.

At time-to-failure of 300–600 sec, MOE increased as MC decreased. The MOE of untreated material increased uniformly across the MOE distribution as it dried from green to 10% (Fig. 2a). For CCA-treated material, a slight flattening in the rate of change in MOE was apparent in the extreme lower tails of the MOE distribution (Fig. 3a).

At time-to-failure of 30–60 sec, the MOE of untreated and CCA-treated material steadily increased at or below the 75th percentile. However, no increase in MOE was noted for either untreated or CCA-treated material above the 90th percentile when going from 15% to 10% MC (Figs. 2b and 3b).

At time-to-failure of 3–6 sec, untreated and CCA-treated material reacted quite differently. About half of the MOE distribution for untreated material plateaued at 15% MC and then showed little or no change on further drying. When untreated material was dried from 15 to 10% MC, the MOE increased over the lower half of the distribution, but did not change over the upper half of the distribution (Fig. 2c). This differential rate of change seemed to be related to rank—the higher in the MOE distribution, the lower the rate of change per change in MC. The CCA-treated material

TABLE 2. *MOE of CCA-treated and untreated No. 1 and better southern pine lumber.*

Time-to-failure (sec)	MC (%)	Treatment	n	Mean (10^6 lb/in.^{2})	SD	Nonparametric percentiles (10^6 lb/in.^{2})						
						5	10	25	50	75	90	95
300	10	unt	111	2.19	0.38	1.61	1.71	1.95	2.17	2.45	2.70	2.83
300	15	unt	109	1.93	0.35	1.36	1.53	1.69	1.94	2.15	2.39	2.56
300	23	unt	111	1.37	0.25	0.98	1.07	1.21	1.37	1.53	1.65	1.81
30	10	unt	111	2.17	0.35	1.57	1.69	1.93	2.19	2.43	2.57	2.73
30	15	unt	111	1.95	0.35	1.39	1.51	1.72	1.90	2.15	2.47	2.63
30	23	unt	111	1.37	0.24	0.97	1.05	1.22	1.41	1.53	1.64	1.73
3	10	unt	110	1.97	0.31	1.52	1.61	1.76	1.93	2.20	2.41	2.50
3	15	unt	37	1.90	0.41	1.26	1.34	1.60	1.87	2.17	2.42	2.67
3	23	unt	110	1.17	0.19	0.82	0.94	1.05	1.17	1.28	1.40	1.48
300	10	cca	111	2.14	0.37	1.51	1.72	1.95	2.13	2.34	2.58	2.76
300	15	cca	112	1.92	0.39	1.38	1.50	1.71	1.89	2.10	2.39	2.51
300	23	cca	112	1.34	0.30	0.92	0.98	1.15	1.31	1.50	1.72	1.89
30	10	cca	111	2.09	0.39	1.48	1.62	1.84	2.08	2.37	2.57	2.74
30	15	cca	111	1.94	0.41	1.39	1.47	1.66	1.89	2.16	2.48	2.81
30	23	cca	110	1.36	0.25	0.99	1.06	1.19	1.35	1.49	1.63	1.80
3	10	cca	112	1.89	0.33	1.43	1.52	1.67	1.84	2.11	2.29	2.41
3	15	cca	33	1.97	0.33	1.40	1.51	1.76	1.99	2.20	2.40	2.42
3	23	cca	111	1.18	0.23	0.81	0.89	1.01	1.18	1.31	1.49	1.56

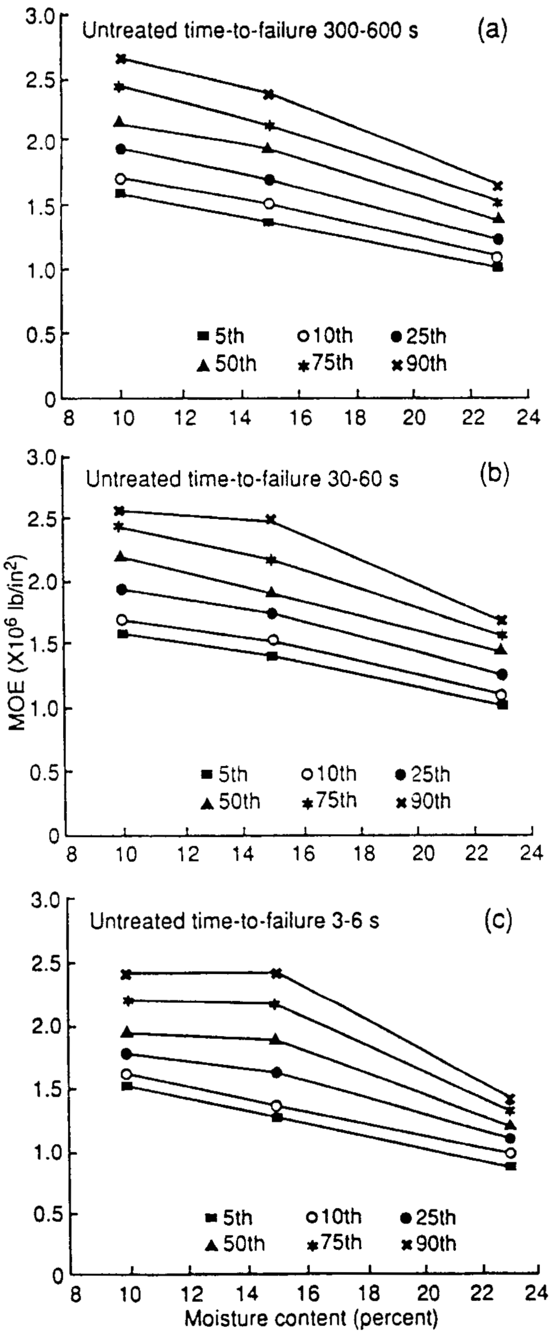

FIG. 2. The effect of moisture on the MOE distribution of untreated lumber at time-to-failure of (a) 300–600 sec, (b) 30–60 sec, and (c) 3–6 sec.

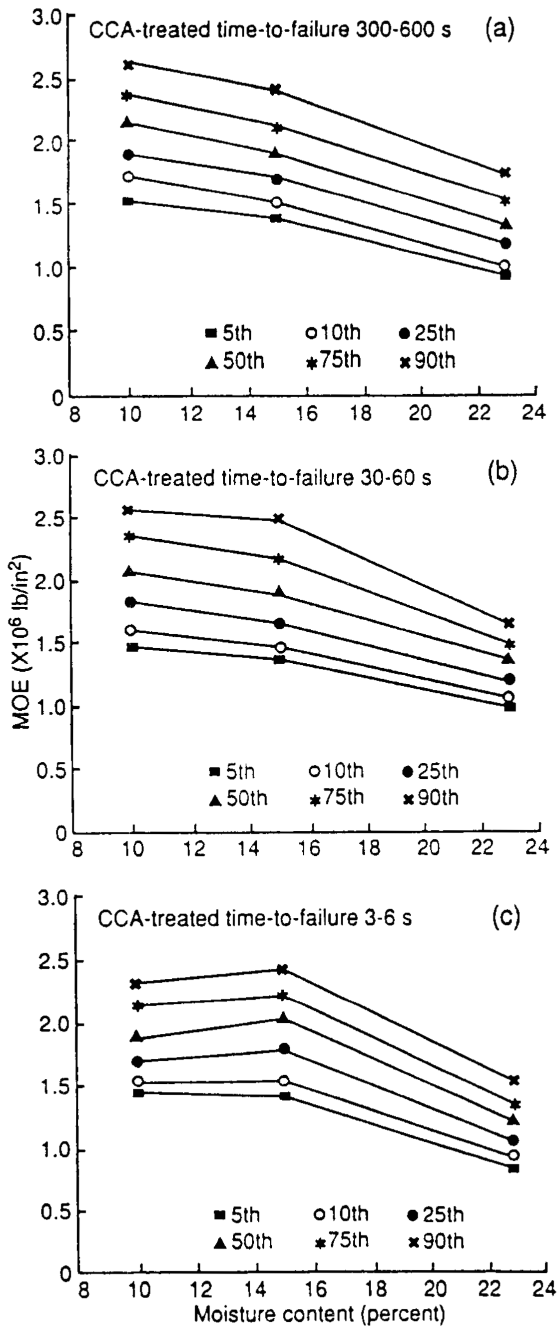

FIG. 3. The effect of moisture on the MOE distribution of CCA-treated lumber at time-to-failure of (a) 300–600 sec, (b) 30–60 sec, and (c) 3–6 sec.

reached MOE maximum at 15% MC, with most of the MOE distribution then steadily decreasing on further drying. In particular, the CCA-treated material exhibited no change in MOE below the 10th percentile, but decreased in MOE above the 10th percentile level (Fig. 3c).

As part of the "MC Effects" Research Program, which supplemented the recent North American In-Grade Testing Program, Green et al. (1986, 1988) and Green and Evans (1989) studied the effect of MC on MOE and decided a linear model fit untreated lumber best. Their data were derived at a time-to-failure of 30–60 sec. From the trends exhibited by the In-Grade data (one rate-of-load and many grade-size-species combinations) and the untreated data from the study reported here (one grade-size-species combination and many rates-of-loading and MC), the linear model for MOE appeared reasonable at time-to-failure of ≥ 30 sec. However, it would appear that the effect of MC on MOE is not entirely independent of rate-of-loading at very short times-to-failure (compare Fig. 2a and 2b to Fig. 2c). Additional work is justified, especially for very dry material subjected to fast rates-of-loading.

For CCA-treated material, a nonlinear model for the effect of MC or MOE seemed more suitable than the linear model of untreated material. It appeared that a continuous quadratic function best described the effect of MC on MOE for CCA-treated lumber. This was based on the distinctly positive, then negative trend in MOE when going from green to 15% to 10% MC, especially at shorter failure times. Conversely, at longer failure times, the average MOE of CCA-treated material probably peaks at some MC just below 10% and then decreases.

Effects of MC on MOR

Summary statistics for MOR of each group are given in Table 3. As MC decreased from green to 15%, MOR increased in a uniform and consistent manner throughout the MOR distribution for both untreated and CCA-treated material at all three failure times (Figs. 4 and 5). However, the effect of reducing MC on MOR was distinctly different at MC levels below 15% than it was at MC levels above 15%. Below 15% MC, the effect of MC on MOR was variable and dependent on treatment, time-to-failure, and percentile level (i.e., rank order) within the strength distribution. Most importantly, the effect of MC on MOR depended more on rank order within the strength distribution than did the effect of MC on MOE.

On drying below 15% MC, untreated lumber increased in strength throughout the upper half of the MOR distribution at all three failure times (Fig. 4). For the lower half of the strength distribution, decreasing MC below 15% had little or no effect on strength at the two longer failure times, and a decidedly negative effect at the shortest time-to-failure of 3–6 sec. Again, as with MOE, this significant Time*MC interaction for untreated MOR clearly shows that the effects of MC on MOR are different at times-to-failure ≥ 30 sec than at times-to-failure of ≤ 6 sec. Recalling that most recent work on the effect of MC on MOR for untreated lumber has been performed at times-to-failure of ≥ 30 sec, additional research on the effect of MC on MOR at very fast loading rates may be needed.

The strength of CCA-treated lumber increased throughout the upper half to three-quarters of the MOR distribution on drying below 15% MC at all three failure times (Fig. 5). For the lower quarter of the strength distribution, decreasing MC below 15% had a negative effect on strength at longer failure times (Fig. 5a and 5b). This negative effect occurred throughout a broader range of the strength distribution as time-to-failure decreased (Fig. 5c).

The MC-induced strength loss reported in this study for CCA-treated material dried to 15% MC was similar in nature and magnitude to that of untreated material that was dried to 10% MC (Green and Evans 1989). Furthermore, the magnitude of the MC-induced strength loss at 10% reported in this study for CCA-treated material was similar to projected strength loss for untreated material at 8% MC

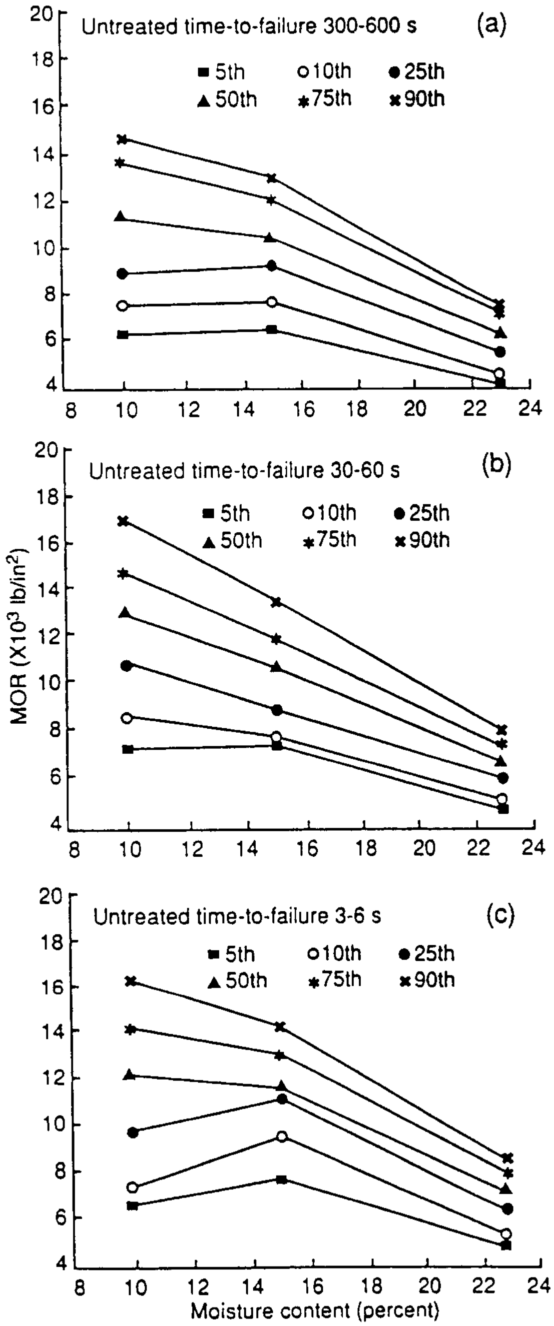

FIG. 4. The effect of moisture on the bending strength (MOR) distribution of untreated lumber at time-to-failure of (a) 300–600 sec, (b) 30–60 sec, and (c) 3–6 sec.

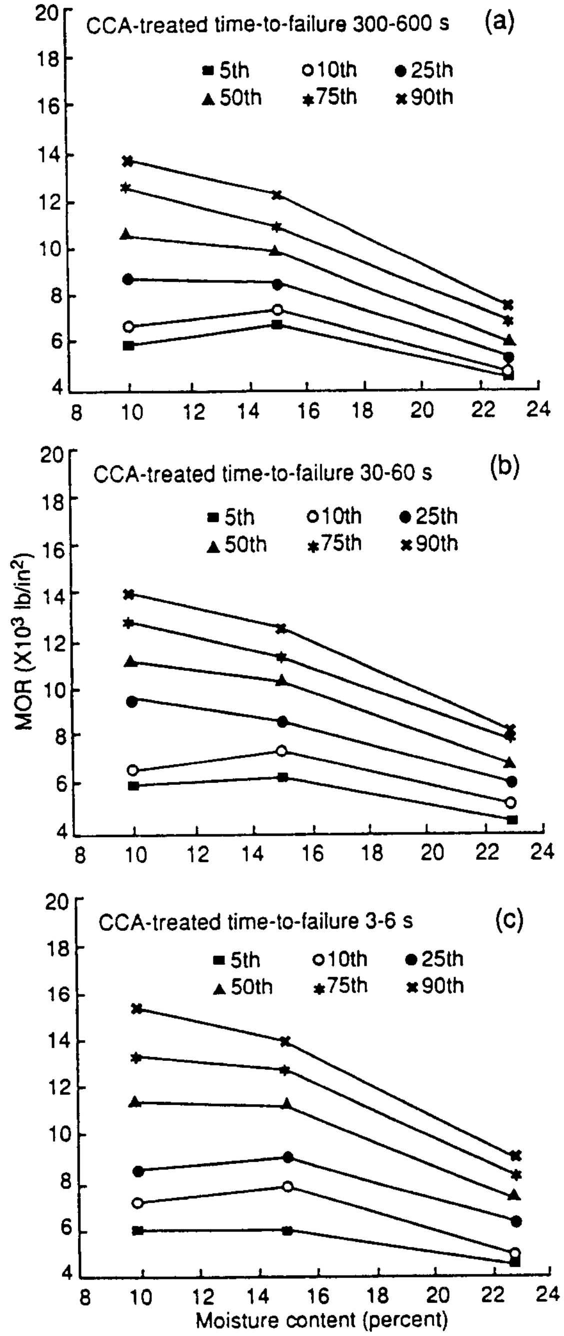

FIG. 5. The effect of moisture on the bending strength (MOR) distribution of CCA-treated lumber at time-to-failure of (a) 300–600 sec, (b) 30–60 sec, and (c) 3–6 sec.

TABLE 3. *MOR of CCA-treated and untreated No. 1 and better southern pine lumber.*

Time-to-failure (sec)	MC (%)	Treatment	n	MOR ($\times 10^3$ lb/in.^{2})[a] Mean	SD	Nonparametric percentiles ($\times 10^3$ lb/in.^{2}) 5	10	25	50	75	90	95
300	10	Untreated	111	11.24	2.86	6.16	7.48	9.02	11.25	13.57	14.76	15.84
	15		109	10.41	2.07	6.42	7.76	9.36	10.43	12.08	12.93	13.37
	23		111	6.22	1.09	4.12	4.39	5.48	6.23	7.12	7.59	7.71
30	10		111	12.81	3.06	7.33	8.71	10.94	13.16	14.81	17.08	17.66
	15		111	10.70	2.06	7.36	7.78	8.95	10.84	11.98	13.58	14.25
	23		111	6.60	1.09	4.62	5.17	5.99	6.73	7.36	7.97	8.32
3	10		110	12.13	3.34	6.75	7.54	9.80	12.19	14.34	16.50	18.01
	15		37	11.86	1.92	7.85	9.57	11.14	11.72	13.16	14.36	14.90
	23		110	7.22	1.27	5.01	5.45	6.36	7.23	8.1	8.76	9.04
300	10	CCA	111	10.42	2.65	5.88	6.71	8.73	10.52	12.51	13.65	14.45
	15		112	9.80	1.86	6.72	7.33	8.49	9.84	10.83	12.27	12.90
	23		112	6.06	1.15	4.44	4.65	5.26	6.03	6.93	7.44	7.90
30	10		111	10.85	2.63	5.87	6.50	9.42	11.09	12.85	14.14	14.97
	15		111	9.99	1.99	6.24	7.30	8.56	10.20	11.36	12.63	13.43
	23		110	6.68	1.27	4.38	5.05	5.78	6.69	7.66	8.10	8.38
3	10		112	11.20	3.16	6.02	7.14	8.63	11.50	13.34	15.30	15.96
	15		33	10.81	2.37	5.96	7.85	9.09	11.22	12.71	13.97	14.25
	23		111	7.07	1.44	4.43	4.91	6.17	7.25	8.19	8.91	9.18

a $\times 10^3$ lb/in.^{2} = 6.895 MPa.

(Green and Evans 1989). This implied that strength loss for lumber is accumulated from both overdrying and treatment. It would further appear plausible that processing and material factors could then be modeled using a cumulative-damage approach (Gerhards 1979), a kinetics approach (Caulfield 1985), or a combination of the two (Winandy 1993b). That model accounts for the apparent accumulation of damage from treatment and post-treatment MC (i.e., dry in-service MC) as a function of the thermo-kinetic severity of the treatment chemical and treatment processing (Winandy 1993b). A detailed report of this latter model is currently in preparation.

TABLE 4. *Proposed service modification factors (C_M) to predict strength loss for treated lumber.*

Service moisture content (percent)	Untreated C_M factor E[a]	F_b[b]	CCA-treated C_M factor E[a]	F_b[b]
>19	0.9	0.85	0.9	0.85
≤19	1.0	1.0	1.0	0.9[c] 1.0[d]
≤12	1.0	1.0	1.0	0.9[c] 1.0[d]

[a] Modulus of elasticity (AFPA 1991).
[b] Allowable stress design value in bending (AFPA 1991).
[c] No. 1 and better grade lumber.
[d] No. 2 grade lumber.

In-service moisture factor (C_M)

Current design values (AFPA 1991), usually derived from ASTM D 1990 (ASTM 1991b), apply to material that is dried below 19% maximum (and 15% average). If a design engineer anticipates that untreated wood will be exposed to MC ≥ 19%, an adjustment, commonly called the wet-use service factor (C_M), of 0.85 for MOR and 0.9 for MOE (Table 4) is applied to modify the design values. However, C_M is really an in-service MC factor. Current modification factors for untreated wood are based on results derived, in part, from the recent "MC Effects" Research Program (Green et al. 1986, 1988; Green and Evans 1989). The current in-service MC adjustments, which are specified in ASTM D 1990, were based on the results of that research program.

The results of the study reported here showed that the difference in the effect of changing MC on MOE seldom exceeds 5% when comparing untreated to treated lumber. Thus, applying the traditional C_M factor for untreated material to CCA-treated material was judged as acceptable for estimating the effects of MC on MOE. However, because of a significant differential effect on MOR from drying CCA-treated material to 10% MC, applying the traditional C_M factor for untreated material to CCA-treated material dried below 15% MC was judged as unwarranted (Fig. 5).

There was no differential effect on bending strength between treated and untreated green material. At 15% MC, however, the differential effect of MC on the bending strength between CCA-treated and untreated lumber was significant at the two shortest failure times (30–60 and 3–6 sec) (Figs. 4 and 5). At 15% MC, CCA treatment reduced bending strength in the lower tails of the distribution about 12%, while median values were reduced 5 to 8%. At 10% MC, the influence of CCA treatment on the effect of MC on strength was significant at all failure times with the bending strength of CCA-treated lumber being reduced over a broader range of the MOR distribution (Figs. 4 and 5). At 10% MC the differences in MOR between CCA-treated and untreated at all percentile levels were generally between 9 and 12%, but did not exceed 14%.

Earlier work concluded that few species-related, preservative-chemical-related, or chemical-retention-related differences existed (Winandy 1991). That work also concluded that material quality factors (such as grade) and processing factors (such as redrying and initial kiln-drying temperature) were critical.

Based on the study reported here, a modified C_M factor for No. 1 and better waterborne-preservative-treated lumber appears necessary. For green material, the traditional C_M factor for MOR of untreated wood adequately described CCA-treated wood bending strength. For No. 1 and better waterborne-preservative-treated material at MC $\leq$ 15%, however, a modified C_M factor of 0.9 on the allowable stress design value in bending should be adopted (Table 4). Based on previous research that showed 12% MC did not affect strength (Winandy 1991), a C_M factor of 1.0 on the design value for No. 2 grade waterborne-preservative-treated lumber was considered acceptable.

CONCLUSIONS

This study shows that a modified wet-use service factor (C_M) of 0.9 is needed to adjust the allowable stress design value in bending for No. 1 and better waterborne-preservative-treated lumber dried to and used at a moisture content (MC) of $\leq$15%. No adjustments beyond those already taken for untreated material are needed for No. 2 grade material or when No. 1 and better waterborne-preservative-treated material is used green (Table 4).

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