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Effect of Fire-Retardant Treatment and Redrying on the Mechanical Properties of Douglas-Fir and Aspen Plywood

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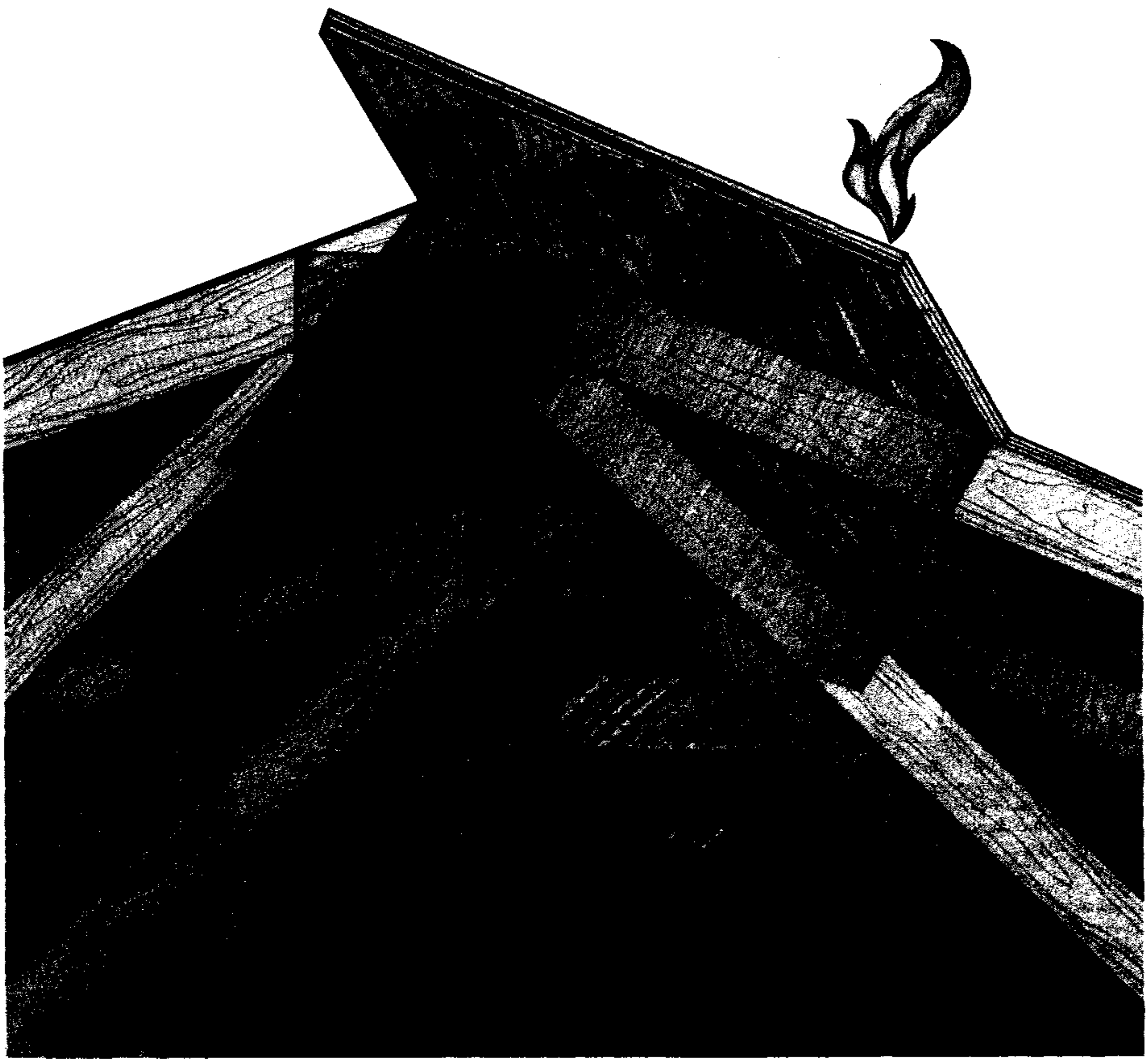

Exterior grades of Douglas-fir and aspen plywood were treated with interior-use fire-retardant (FR) chemicals and redried after treatment using several kiln-drying or press-drying temperatures. FR treatments included borax-boric acid, chromated zinc chloride, minalith, pyresote, and a commercial proprietary formulation. Bending strength (MOR), load-carrying capacity (RZ), modulus of elasticity (MOE), stiffness (EI), work to maximum load (WML), and horizontal (rolling) shear strength (TAU) were evaluated. With the exception of chromated zinc chloride, all of the FR treatments appeared to have similar "relative" effects on the mechanical properties tested. Chromated zinc chloride treatment reduced strength and stiffness more than the other FR treatments tested. While MOE and EI were not affected by most combinations of treatment and redrying, all five FR treatments followed by post-treatment kiln-drying temperatures in excess of 160 °F considerably reduced MOR, RZ, and WML for both species and TAU for Douglas-fir. Press drying at temperatures of 250 °F appeared to have a comparable effect to kiln-drying after treatment temperatures of 180 to 200 °F. Except for the differential effect on TAU, FR treatment and redrying had a similar effect on the two species of plywood tested.

Keywords: Fire retardants, structural plywood, bending strength, shear strength, Douglas-fir, aspen, borax-boric acid, chromated zinc chloride, minalith, pyresote, kiln-drying, press-drying, plywood, panel products.

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FPL-RP-485 Errata

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Errata

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Page 6, Figure 2

The MOE values on the vertical axes of Figure 2 should be divided by 2; that is, MOE should range from 0 to 2.5 million psi.

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Effect of Fire-Retardant Treatment and Redrying on the Mechanical Properties of Douglas-Fir and Aspen Plywood

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Introduction

For many types of multifamily residential and nonresidential constructions, building codes require that softwood lumber and plywood be treated with fire-retardant (FR) chemicals. Although such treatment effectively retards combustion, it also reduces strength. Strength reduction can be magnified when the lumber or plywood is improperly treated and dried. To complicate matters, little is known about the effects of FR treatment and subsequent redrying on low-density hardwood species, now commonly used as core stock in commercial softwood-faced plywood.

FR treatments yield a wood product with a high moisture content. The wood must be dried to achieve dimensional stabilization and reduce shipping weight. Kiln-drying after treatment (KDAT) can reduce the strength of the treated wood unless the redrying is accomplished under relatively mild drying conditions (Adams et al. 1979; Gerhards 1970; Graham 1964; Jessome 1962; Johnson 1967, 1979; King and Matteson 1961). To minimize strength loss, current standards of the American Wood-Preservers' Association (AWPA 1986a) for FR-treated plywood require that the dry-bulb kiln temperature shall not exceed 160 °F until the average moisture content of the wood has dropped to 25 percent or less.

The primary objective of our study was to assess the effect of various FR treatments and redrying techniques on the drying time and degrade (e.g., warp, checking) of FR-treated plywood. This aspect of the study has been previously reported (Lee and Schaffer 1982). The secondary objective of this study, and the specific objective of this report, was to determine the effects of various FR treatments and redrying regimes on the bending and horizontal rolling shear properties of two species of exterior-grade, structural plywood. We also investigated the effect of press drying on the strength properties of FR-treated plywood. The statistical design of this study emphasized our primary objective and gave less importance to our secondary objective. Consequently, the statistical analysis of data reported here was limited, as will be discussed in Results and Discussion.

Most FR chemicals alter the treated wood's hygroscopicity and mechanical properties; equilibrium moisture content (EMC) and volume are usually increased, and strength is usually reduced. However, strength loss should not always be construed as an equivalent loss in load-carrying capacity. For example, a FR-treated panel could ostensibly be reduced in bending strength but have increased load-carrying capacity because swelling results in an increased section modulus (Lehmann and Schaffer 1980). Because FR-treated plywood commonly serves as a structural panel, its load-carrying capacity (RZ) and stiffness (El) are often emphasized. Reductions in bending strength (MOR) and modulus of elasticity (MOE) are usually of secondary importance, although they are of interest in assessing treatment effects. This important distinction between bending strength and load-carrying capacity will be addressed later in this report.

Historically, an increase in EMC at high relative humidity (RH) has been a major problem in the use of FR-treated lumber and plywood. For example, in one study red pine lumber treated with various FR formulations and held at 77 °F (25 °C) and 60 percent RH reached an EMC of 9 to 13 percent (depending on FR treatment and adsorption/desorption condition) while untreated controls reached an EMC of 8 to 11 percent: at 77 °F and 80 percent RH, FR-treated red pine reached an EMC of 19 to 27 percent and controls an EMC of 13 to 14 percent (McKnight 1962). Although the slightly higher EMC of most FR-treated wood does not cause problems at RH below 70 to 75 percent, moisture-related problems may occur at RH above these levels. The higher EMC can cause fasteners to corrode and loosen from excessive joint swelling and shrinkage under changing conditions. Recently, a series of newer "second-generation" FR treatments have been developed that claim to have overcome these problems. These second-generation proprietary formulations were not included in our study because they were not commercially available at that time.

The effect of FR treatments and subsequent redrying on wood strength can be categorized by the FR used and the maximum dry-bulb temperature in the kiln (table 1). If FR-treated wood is kiln-dried, the effect on MOR, MOE, and especially work to maximum load (WML) can be significant (Gerhards 1970). The literature (table 1) suggests reductions in engineering design stresses for FR treatment and kiln drying consistent with the modification factors recommended by the National Forest Products Association NDS (1986) for FR-treated lumber (table 2).

Current AWPA (1986a, 1986b) specifications for redrying FR-treated wood dictate that dry-bulb temperatures during kiln drying should not exceed 160 °F (71 °C) until the mean treated-wood moisture content is 25 percent or less. This requirement recognizes that elevated temperatures interact with the excess moisture in freshly treated wood to accelerate thermal degradation. The presence of water promotes hydrolysis in untreated wood at temperatures exceeding 212 °F (100 °C). For example in untreated wood, Stamm (1964) estimated that a kiln load of softwood heated for 2 days at 160 °F (71 °C) and an additional 5 days at 200 °F (93 °C) would result in a reduction in MOR of 3.0 percent. In the first 2 days of drying at 180 °F, while the wood still contained free moisture, Stamm estimated the incremental loss at 2.5 percent, with an additional loss of only 0.5 percent in the next 5.day period at 200 °F because moisture content would be far lower. In addition, the presence of some FR can cause wood hydrolysis and thermal degradation at even lower temperature levels (Eickner 1986). Unfortunately there are no reported fundamental studies that quantify the effect of both the presence of moisture and heat for FR-treated wood.

Steam- or oil-heated platens at temperatures ranging from 250 °F (121 °C) to as high as 500 °F (260 °C) are commonly used to press dry the panels. Because contact pressure between platens and the material influences wood compaction and drying rates, a platen pressure of 50 pounds per square inch (lb/in^2) is commonly suggested as an optimum tradeoff. Still, with green wood the loss in thickness by compaction at 50 lb/in^2 may be twice that observed after air or kiln drying. This shrinkage could significantly influence load-carrying capacity and stiffness in bending; this problem was more thoroughly discussed in a previous report (Lee and Schaffer 1982).

The elevated temperatures employed in press drying might also be expected to affect strength. Yet, limited evidence exists that press drying softwood laminated-veneer lumber at platen temperatures of 375 °F (190 °C) and contact pressures of 50 lb/in^2 does not affect shear strength compared to other kiln-drying methods (Forest Products Laboratory 1977). Toughness, a sensitive strength property to treatment effects, was shown to be comparable in press-dried and kiln-dried hardwoods (Hittmeier et al. 1968). Information on the effects of press drying on the strength and stiffness of FR-treated wood is not available.

Methods

Design

Two species (Douglas-fir and aspen) of 5/8-inch-thick, five-ply, A-C exterior-grade plywood were evaluated. The test panels were cut from commercially manufactured 4- by 4-foot aspen plywood and 4- by 8-foot Douglas-fir plywood. For each species, we selected 280 12- by 24-inch panels with no visible defects. These panels were randomly assigned to individual treatment-drying groups (sample sizes of four panels per group except for control and water-treated/air-dried groups) to distribute within-panel and between-panel variability resulting from differences in the original plywood sheets. The panels were then equilibrated at 74 °F and 65 percent RH for several weeks, treated, and redried as described below:

Group	Treatment	Drying[1] Control	Air	Kiln[2]	Press[3]
BRX	Borax-boric acid			28	12
CZC	Chromated zinc chloride			28	12
MIN	Minalith			28	12
PYR	Pyresote			28	12
NCF	Commercial proprietary formulation			28	12
H_2O	Water		20	28	12
CTL	Control	20			

[1]Number of panels treated for each species-treatment. drying combination.

[2]Seven levels (120, 140, 160, 180, 200, 230, and 260 °F); 4 panels per level.

[3]Three levels (250, 300, and 350 °F); 4 panels per level.

Treatment

The H_2O group of panels was treated full-cell to a water retention of 32.9 pounds per cubic foot (lb/ft^3). Based on this retention, panels for the BRX, CZC, MIN, and PYR formulations were treated full-cell to target retention of 5 lb/ft^3. The NCF panels were treated in accordance with the manufacturer's recommendation. Except for the proprietary NCF, the specific FR formulations used are given in table 3.

Drying

For every species-treatment combination, four plywood panels were kiln-dried after treatment at each of seven levels: 120°/115° (dry bulb/wet bulb), 140°/135°, 160°/155°, 180°/175°, 200°/190°, 230°/190°, or 260°/190°F. Similarly, for every species-treatment combination, four plywood panels were press-dried at each of three platen temperatures: 250, 300, or 350 °F. Platen pressures of 50 lb/in^2 were employed at each press-dry temperature. Twenty water-treated specimens for each species were air-dried at 80 °F. A more detailed account of the drying procedures and their impacts on drying degrade has been previously reported (Lee and Schaffer 1982).

Following drying, all specimens were equilibrated at 74 °F and 65 percent RH prior to mechanical testing. These conditions produced about a 12 percent EMC in the untreated wood.

Mechanical Property Tests

Bending Test

Each 12- by 24-inch panel was subjected to third-point bending on a 22-inch span loaded across the 12-inch dimension at a load rate of 0.15 inch per minute (fig. 1). Load and resulting center-span deflection were recorded until the maximum load was obtained. MOR, MOE, WML, RZ, and EI were calculated for each panel.

Horizontal (Rolling) Shear Test

After the bending test, two 3- by 6-inch bending specimens were cut from undamaged portions of each 12- by 24-inch panel and subjected to center-point load on a 4-inch span to maximum load. The 6.4 span-to-depth ratio produced a horizontal (rolling) shear failure in the center ply rather than a bending failure in the outer ply of each specimen. The maximum horizontal shear stress (TAU) was calculated employing a standard homogeneous strength-of materials shear-strength formula. The two observations of TAU from each panel bending test were averaged because (1) there was far less within-panel variability than between-panel variability, and (2) averaging allowed direct comparison of shear strength to other mechanical properties.

Results and Discussion

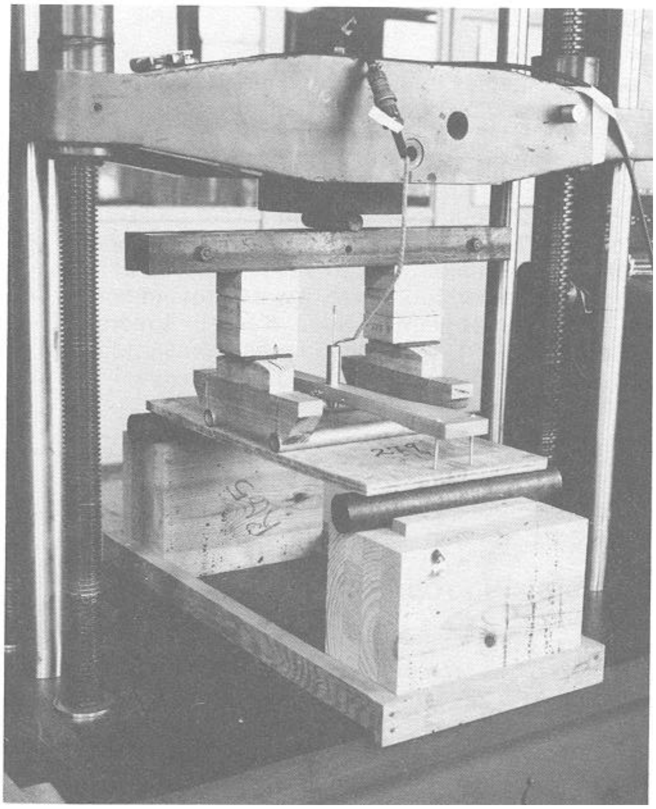

Figure 1—Bending test setup for evaluating bending strength and stiffness of 12- by 24-inch plywood panels. (M 150 381-6)

The sensitivity of statistical analysis of the data to treatment-drying effects was restricted by the small sample sizes employed. This resulted from the secondary emphasis placed on assessing mechanical property effects in the experimental design. Adding to the problem was our inability to differentiate within-panel variability from between-panel variability. (Recall that specimens were randomly rather than systematically assigned to groups to evenly distribute number of specimens from individual panels among the groups.) These factors reduced our ability to discern treatment and/or drying effects from natural variability. Still, the overall results merit discussion because of the general lack of information on the effects of FR treatment and redrying on mechanical properties and because of the potential impact of the results on safe engineering design.

While the literature suggests that FR treatment has a different effect on MOR and RZ and on MOE and El because of chemical bulking, no differences of practical importance were noted in our study. Apparently the increase in section modulus from bulking was not sufficient to offset the effects of FR treatment on strength and MOE. Thus, the following discussions of the effects of FR treatments upon MOR and MOE also apply to RZ and El, respectively.

For each species-treatment combination, average test results (MOE, MOR, WML, and TAU) versus redrying temperature are shown in figures 2 to 5. Several significant treatment-drying interactions occurred (table 4). For example, note that interactions occurred between CZC and NCF treatments for MOE of press-dried Douglas-fir (fig. 2) between CZC and H_2O treatments for MOR of kiln-dried aspen (fig. 3), and between CZC and PYR treatments for TAU of press-dried aspen (fig. 5). With closer inspection, additional interactions can also be noted.

In an attempt to enhance statistical analysis, an analysis of covariance (COV) was considered involving two traditional mechanical property covariates, specific gravity (SG) and moisture content (MC). But the use of COV was rejected because both covariates are themselves significantly influenced by FR treatment. We also considered grouping redrying conditions that exhibited statistically similar mechanical property responses. We thought that the grouping process might effectively reduce treatment-drying interaction and increase replication; however, it did not entirely eliminate the interactions. Thus, the use of grouping was rejected.

Keeping in mind that interactions in the data limit interpretation (table 4), we will highlight the important general trends in the data while also showing the statistical limits of these data. The results of Tukey tests for mean redrying effect on MOR, WML, and TAU of treated aspen and Douglas-fir plywood are shown in tables 5-7. These results highlight the insensitivity of the analyses to historically significant trends (table 1). The magnitude and consistently negative trend of the FR treatment-redrying effect in our data (tables 8, 9) leads us to suspect that the limited number of samples used was the primary cause of the statistical insensitivity (tables 5-7). Still, practical and conclusive results can be distinguished by prudently considering the effect of each treatment and drying factor on individual species-property combinations (table 10). Using table 10 as a guide to what we perceive as being practically important, we can finally discuss overall trends.

Species Effects

Both species of plywood were affected by FR and redrying to about the same relative degree except for a differential effect on TAU; TAU was reduced in Douglas-fir but not in aspen (table 10). Overall, the properties of treated aspen plywood were slightly higher than those of Douglas-fir plywood (figs. 2-5). These differences probably reflect the initial veneer quality or phenolic-adhesive contents because the specific gravity of the Douglas-fir controls was actually higher than that of aspen (0.52 versus 0.49).

Treatment Effects

In general, FR treatment did not affect the MOE of both species and the TAU of aspen, whereas it reduced the other mechanical properties of both species (tables 8-10). CZC treatment had a far greater negative effect on almost every species-property combination studied (compared to controls) than did the other FR treatments or water treatment (table 10). It is probable that the high level of chloride in CZC treatment promoted hydrolysis via an intermediate formation of hydrochloric acid.

With few exceptions, the minalith (MIN), pyresote (PYR), borax-boric acid (BRX), and the nondisclosed commercial proprietary formulation (NCF) all apparently had a comparable "relative" effect upon each of the properties studied (table 10). Water treatment had less effect than FR treatments, but a greater effect than no treatment at all (figs. 2.5).

Drying Effects

MOR, WML, and TAU were generally reduced as redrying temperatures increased (tables 8 and 9). At redrying temperatures of 160 °F or below, the effects of FR treatment on both plywood species studied were generally comparable to those cited in previous reports (table 1). However, when FR treatment was followed by kiln-drying temperatures in excess of 160 °F, each of the five FR treatments studied seemed to further reduce MOR, WML, and TAU (tables 8-10).

Press drying after FR treatment was apparently less degrading towards mechanical properties than kiln drying at nearly equivalent temperature. Still, press drying was most often more degrading to mechanical properties than KDAT temperatures $\leq$160 °F. At 250 °F, press drying apparently had about the same relative effect on strength as KDAT temperatures of 180 to 200 °F (tables 8, 9).

These findings, while directly applicable to only FR-treated plywood, appear to reaffirm support for the 160 °F AWPA redrying temperature limitation during the high MC periods of the redrying process.

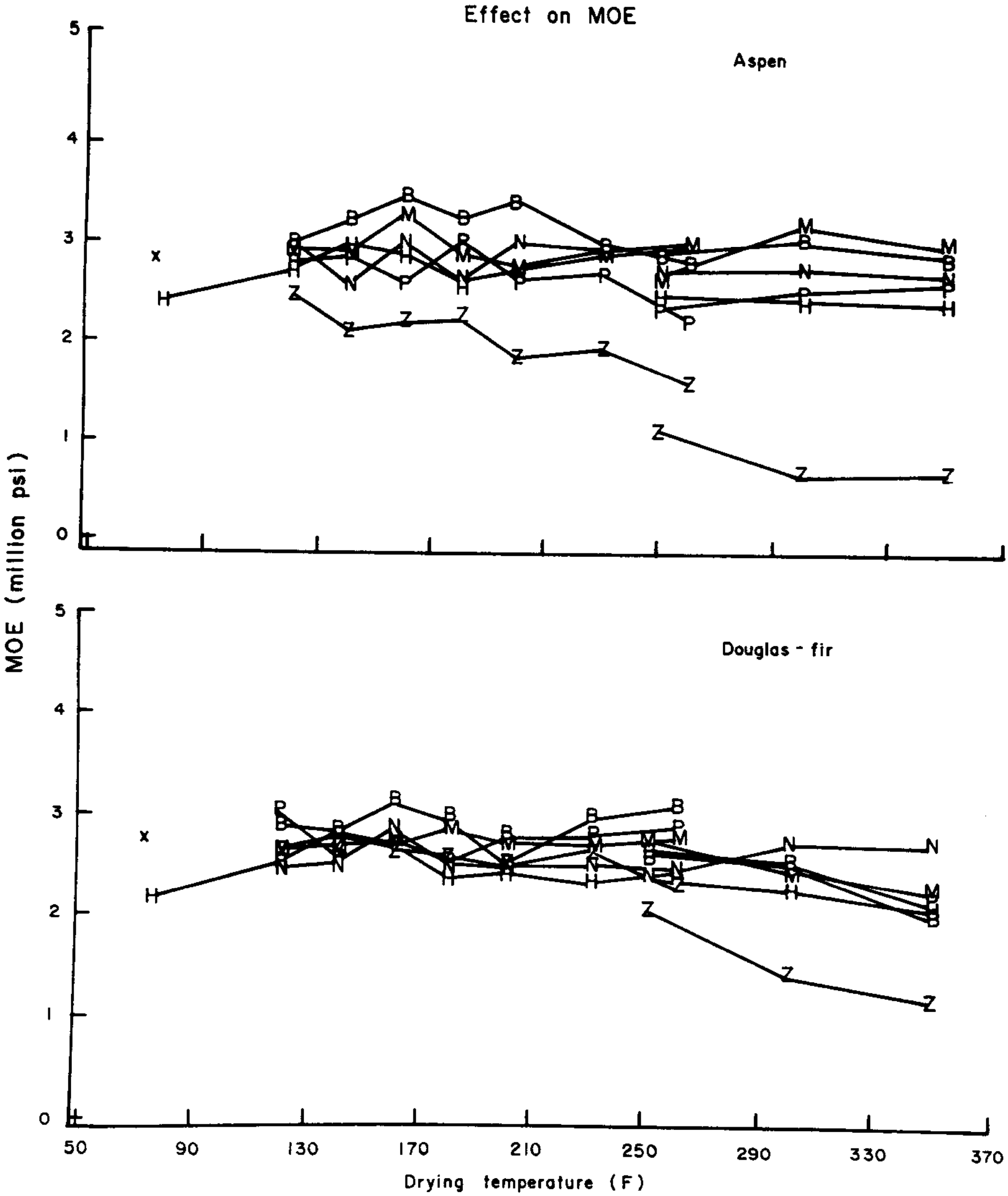

Figure 2—Effects of various fire-retardant treatments and redrying conditions on average values of modulus of elasticity (MOE) for $^{5}/_{8}$-inch aspen and Douglas-fir plywood. B = borax-boric acid, H = H_2O, M = minalith, N = NCF (commercial proprietary formulation), P = pyresote, x = control, *Z = chromated zinc chloride. (ML87 5474)*

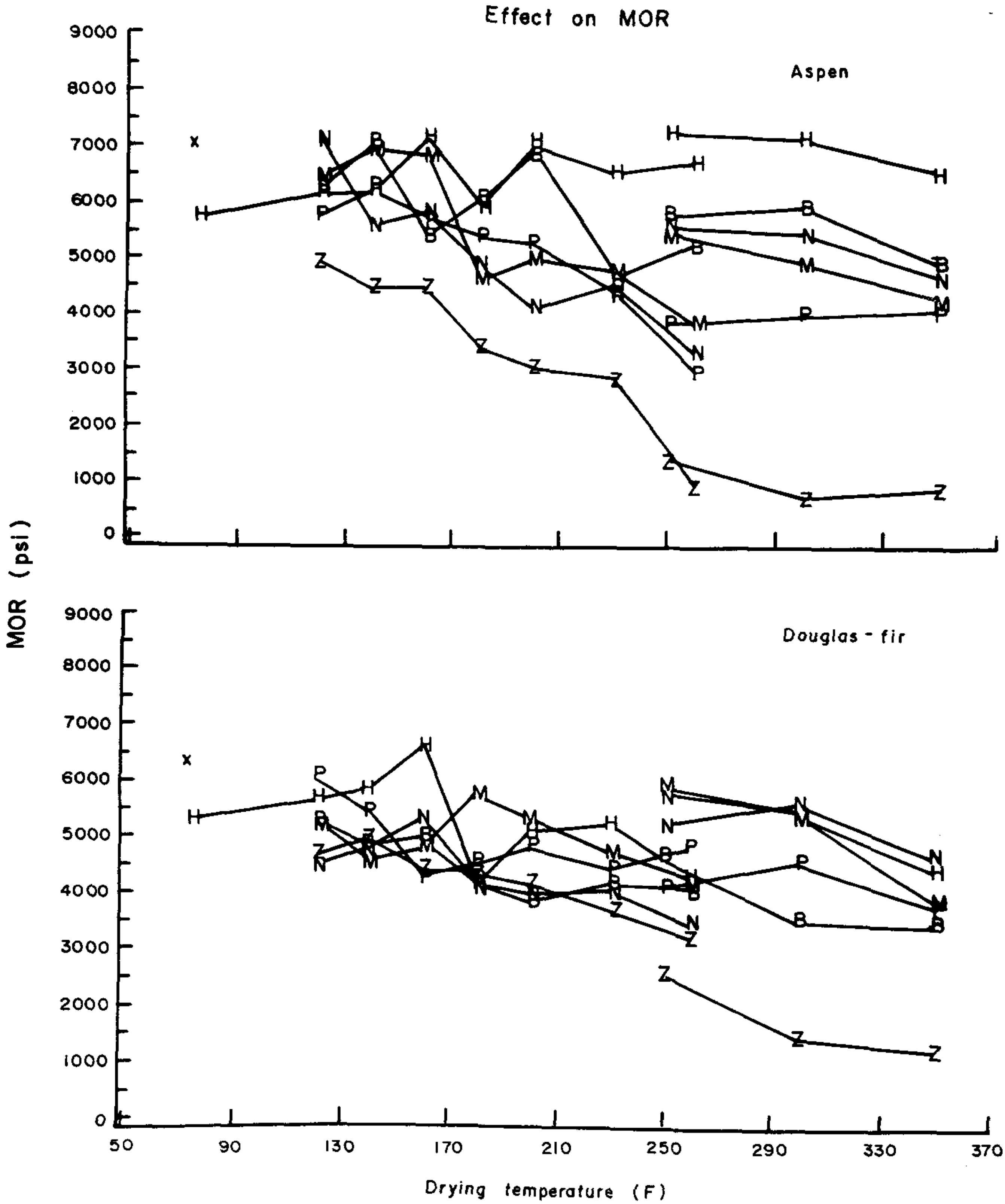

Figure 3—Effects of various fire-retardant treatments and redrying conditions on average values of modulus of rupture (MOR) for ⁵⁄₈-inch aspen and Douglas-fir plywood. (See figure 2 for letter designations.) (ML87 5475)

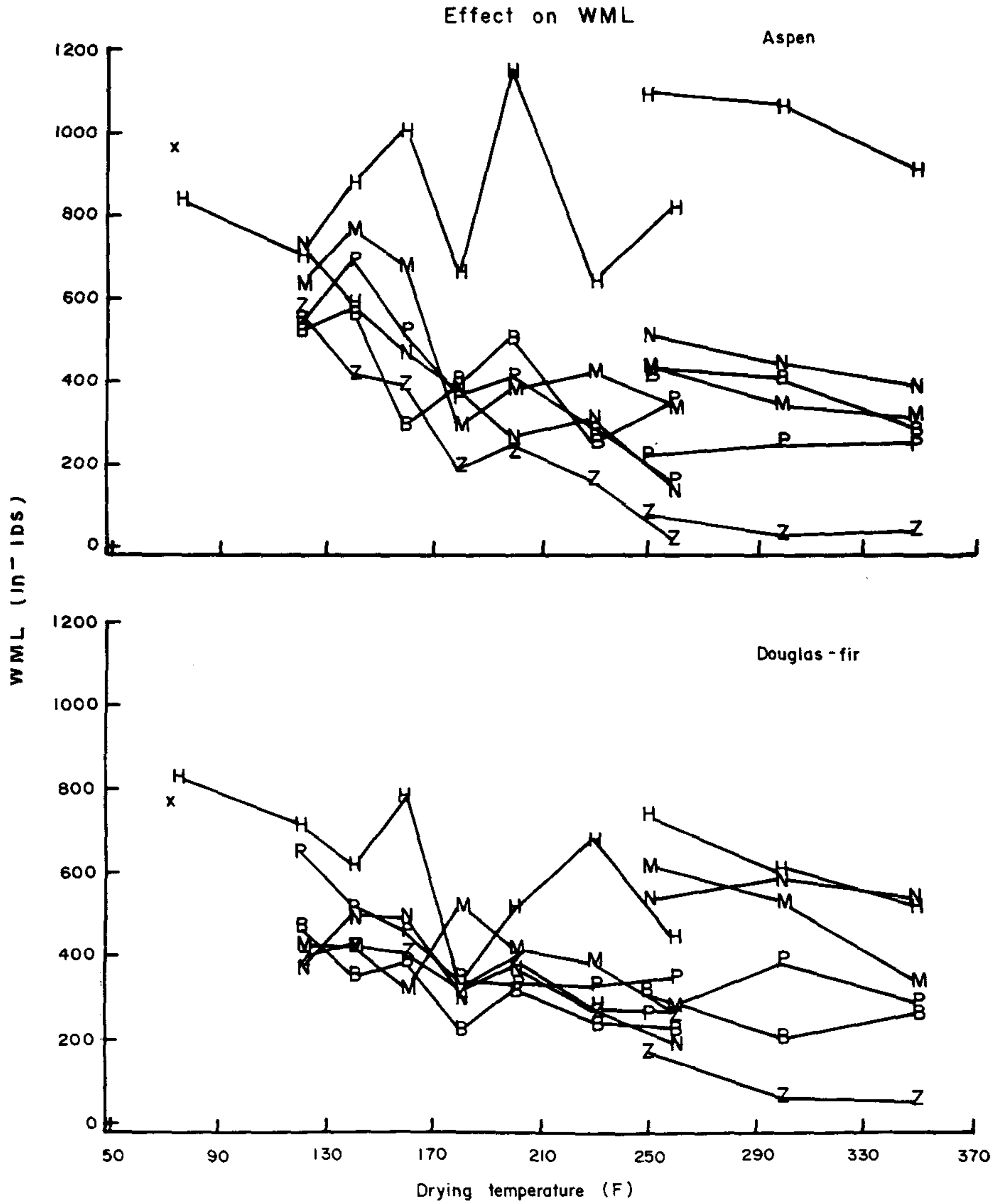

Figure 4—Effects of various fire-retardant treatments and redrying conditions on average values of work to maximum load (WML) for $^5/_8$-inch aspen and Douglas-fir plywood. (See figure 2 for letter designations.) (ML87 5476)

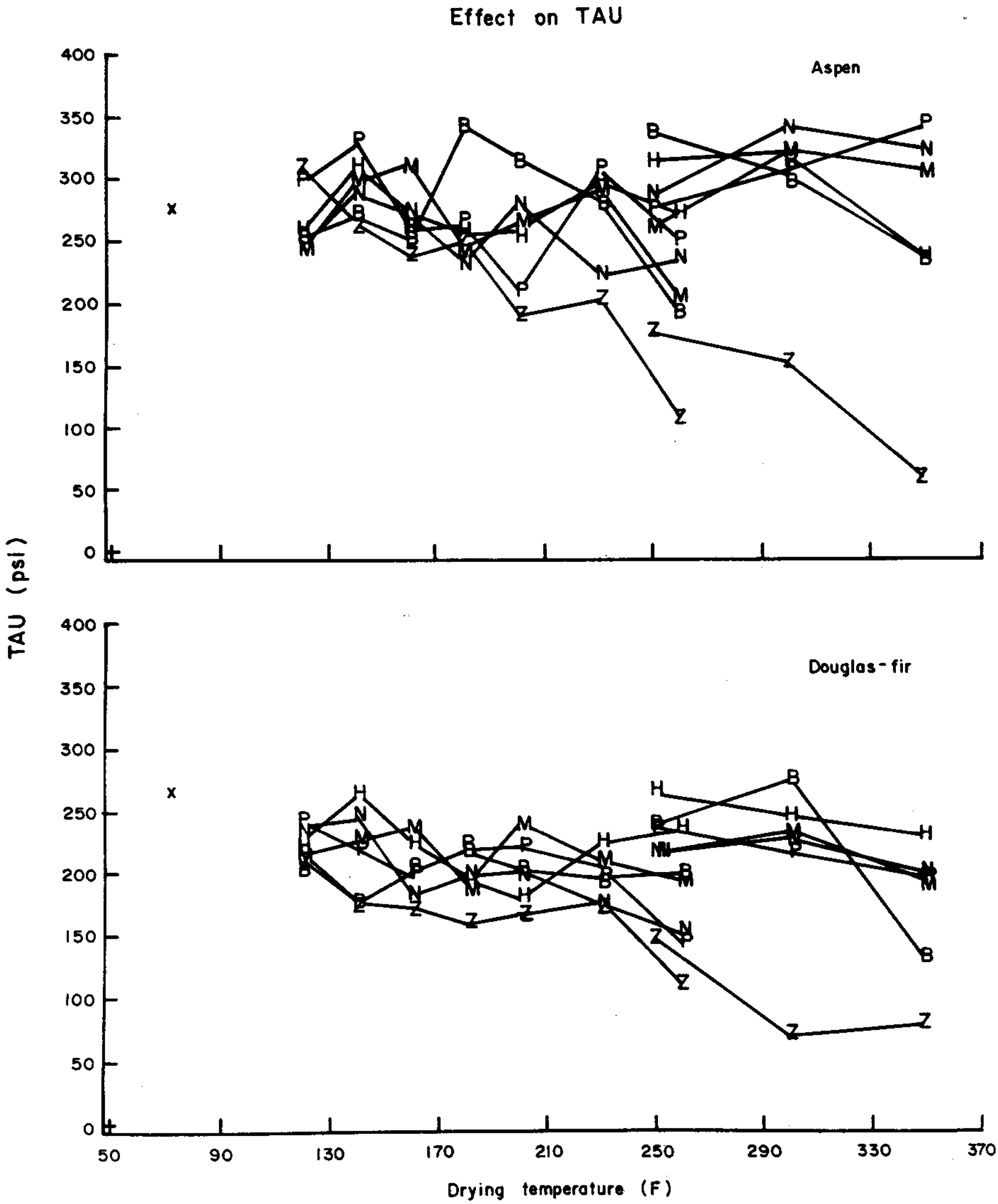

Figure 5—Effects of various fire-retardant treatments and redrying conditions on average values of horizontal rolling shear (TAU) for $^5/_8$-inch aspen and Douglas-fir plywood. (See figure 2 for letter designations.) (ML87 5477)

Conclusions

Aspen and Douglas-fir 5/8-inch plywood were treated with various FR chemicals and then either kiln-dried (seven temperature levels) or press-dried (three temperature levels) after treatment. Each specimen was tested in bending and in rolling shear; several material properties were analyzed.

Overall, no practical differences were found between the effects of FR treatment and redrying on the two species of plywood studied. Mechanical properties were apparently most degraded by CZC treatment and least degraded by water treatment. The effect of the other treatments—BRX, MIN, NCF, and PYR—lay in between that of CZC and water. Except for TAU, both species were comparably affected by the five FR treatments when subsequently redried at temperatures ≤160 °F. For both species, FR treatment did not affect MOE and reduced MOR and WML. TAU was unaffected in aspen specimens and reduced in Douglas-fir specimens. However, when FR-treated plywood was redried at >160 °F, each of the five FR treatments studied further reduced MOR, WML, and TAU (tables 8, 9). Press-drying at 250 °F appeared to have a comparable effect to KDAT temperatures of 180 to 200 °F.

The American Plywood Association (APA) recently removed its long-recommended design modification factors for FR treatment of - 17 percent for design stresses and - 10 percent for MOE from its Plywood Design Specification (APA 1985); they now specify that the design engineer should obtain design stress modification factors from the FR formulators. The National Forest Products Association (NFPA) recently considered the same approach in its new National Design Specification for Wood Construction (NFPA 1986), but instead decided on the modification factors shown in table 2 and recommended a quality control procedure for assuring those FR-treated lumber properties (Appendix Q, NFPA 1986). Our data indicate that in the absence of published modification factors for plywood, it seems prudent to support reductions in allowable bending and shear stresses for FR-treated plywood similar to those currently required for FR-treated lumber.

Finally, because it appears that post-treatment redrying at >160 °F significantly reduces the strength of FR-treated products and because temperatures >150 °F permanently reduce the strength of untreated wood (MacLean 1945, 1951, 1953), we recommend that extended exposure of FR-treated wood to temperatures >150 °F should especially be avoided.

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Table 1—Published information on the effects of fire-retardant treatments on mechanical properties expressed as percent change from their respective untreated controls

Author/manufacturer	Year	Chemical[1]	Species[2]	Redry temperature	MOR	MOE	Energy[3]	C-par[4]	T-par[5]
				°F	*Pct*				
Adams, Moore, Brazier	1979	Noncom X[6,7]	Sects pine	221	+ 26	– –	– –		
		FRT		140	– 20	– –	– 30		
				198	– 48	– –	– 65		
Countryman	1957	MIN	D. fir ply	– –	– 8	– 5	– 57		
Gerhards	1970	AP	S. pine	140	– 19	– 19	– 21		
		APAS		Kiln	– 17	– 3	– 44		
					– 16	– 3	– 45		
		FRT	Combo.	– –	– 13	– 5	– 34		
			S. pine	Kiln	– 11	– 8	– 26		
					– 17	– 13	– 33		
					– 10	– 8	– 40		
		Noncom X[6]	D. fir		– 16	– 5	– 32		
			S. pine		– 14	– 8	– 24		
			Glulam	Kiln	– 12	– 2	– –		
		PYR	S. pine		– 10	– 8	– 28		
			D. fir		– 17	– 5	– 32		
				Air	– 29	– 12	– 37		
Graham	1964	Borax	D. fir	Air	+ 20	+ 19			
		AS			– 3	+ 4			
		Type B			+ 2	+ 9			
		Type C			+ 6	+ 9			
		Type D			– 2	+ 4			
		FRT			– 4	– 1			
		FRT			– 5	– 1			
Jessome	1962	APAS	Red pine	150	– 29	– 5	– 62		
				Kiln	– 23	– 5	– 55		
			D. fir	Kiln	– 3	– 1	– 24		
				Kiln	– 13	– 1	– 29		
			D. fir ply	Kiln	– 15	– 9	– 6		
				Kiln	– 16	– 9	– 2		
		ZAB	Red pine	150	– 10	+ 2	– 42		
			D. fir	Kiln	– 2	+ 2	– 12		
			D. fir ply	Kiln	– 13	– 10	– 8		
Johnson	1967	FRT	D. fir	Air	– 11	– 5	– 55		
				Air	– 5	0	– –		
				140	– 15	– 3	– –		
				158	– 14	– 1	– –		
King and Matteson	1961	FRT	D. fir ply	75	– 6	– 6			
					– 11	– 24	– 31		
HOOVER Universal TWP, Inc.	1984	Pro-Tex[6]	Combo.	160	– 10	– 1	– 21	– 5	– 9
Koppers Cc.	1985	Dricon[6]	S. pine	160	– 10	0	– 26	– 2	– 7
			D. fir		– 9	0	– 11	– 5	– 12
			Spruce		0	0	– 10	0	0
			S. pine ply		– 2	– 3	0	0	
			D. fir ply		0	– 5	0	0	
OSMOSE Inc., W. Pres. Div.	1984	Fl.Pf.LH[6]	Combo.	180	– 10	0	– –	– –	– 25

[1] AP = Ammonium phosphate; AS = ammonium sulfate; APAS = AP + AS; Borax = boric acid + sodium tetraborate; FRT = unidentified; ZAB = zinc ammonium borate.

[2] Combo. = various species; D. fir = Douglas-fir; S. pine = southern pine.

[3] Energy-related properties (include work, toughness, impact bending, etc.).

[4] Compression parallel-to-grain.

[5] Tension parallel-to-grain.

[6] Proprietary commercial formulation.

[7] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 2—Fire-retardant-treatment adjustment factors for modification of allowable design stresses from the National Design Specification for Wood Construction[1]

Property	Adjustment factor
Extreme fiber in bending	0.85
Tension parallel-to-grain	.80
Horizontal shear	.90
Compression perpendicular-to-grain	.90
Compression parallel-to-grain	.90
Modulus of elasticity	.90
Fastener design loads	.90

[1] National Forest Products Association, 1986.

Table 3—Individual flre-retardant chemical compositions

Chemicals	Percent
Borax-boric acid (BRX)	
Borax ($Na_2B_4O_7$)	60
Boric acid (H_3BO_3)	40
Chromated zinc chloride (CZC)	
Chromated zinc chloride	80
Ammonium sulfate ($(NH_4)_2SO_4$)	10
Boric acid (H_3BO_3)	10
Minalith (MIN)	
Diammonium phosphate ($(NH_4)_2HPO_4$)	10
Ammonium sulfate ($(NH_4)_2SO_4$)	60
Sodium tetraborate anhydrous ($Na_2B_4O_7$)	10
Boric acid (H_3BO_3)	20
Pyresote (PYR)	
Zinc chloride ($ZnCl_2$)	35
Ammonium sulfate ($(NH_4)_2SO_4$)	35
Boric acid (H_3BO_3)	25
Sodium dichromate ($Na_2Cr_2O_7H_2O$)	5

Table 4—Results of an analysis of variance on four mechanical properties tested for aspen and Douglas-fir plywood[1]

Source	Degrees of freedom	MOE	MOR	WML	TAU
ASPEN AND DOUGLAS-FIR					
Species (S)	1	0.0006	0.0001	0.0007	0.0000
Chemical (C)	5	.0000	.0000	.0000	.0001
Drying (D)	9	.0001	.0001	.0001	.0001
S * C	5	.0001	.0001	.0001	.1555
S * D	9	.0962	.1357	.3040	.1425
C * D	45	.0001	.0001	.0024	.0001
S*C*D	45	.0108	.0369	.0713	.0025
R-square		.7448	.6906	.6328	.7268
ASPEN ONLY					
C	5	.0000	.0000	.0001	.0001
D	9	.0001	.0001	.0001	.0001
C * D	45	.0001	.0001	.0765	.0001
R-square		.8155	.7940	.6551	.6563
DOUGLAS-FIR ONLY					
C	5	.0001	.0001	.0001	.0001
D	9	.0001	.0001	.0001	.0001
C * D	45	.0001	.0208	.0012	.0001
R-square		.6003	.4958	.5621	.6406

[1] Untreated control and air-dried water-treated control not included.

Table 5—Results of Tukey's test of means for modulus of rupture (MOR) of aspen and Douglas-fir plywood after treatment[1,2]

Treatment	R^2	Drying temperature											
ASPEN													
BRX	0.409	140	CTL	200	120	180	300	250	160	260	350	230	
NCF	.694	120	CTL	160	140	250	300	180	350	230	200	260	
CZC	.920	CTL	120	160	140	180	200	230	250	260	350	300	
MIN	.657	CTL	140	160	120	250	200	300	230	180	350	260	
PYR	.669	CTL	140	160	120	180	200	230	350	300	250	260	
H_2O	.257	250	160	300	200	CTL	260	230	350	140	120	180	75
DOUGLAS-FIR													
BRX	.462	CTL	120	160	140	250	180	230	260	200	300	350	
NCF	.431	CTL	300	160	250	140	350	120	180	230	200	260	
CZC	.689	CTL	140	120	160	180	200	230	260	250	300	350	
MIN	.317	CTL	250	180	300	200	120	160	230	140	260	350	
PYR	.307	CTL	120	140	200	260	300	180	230	160	250	350	
H_2O	.232	160	CTL	140	250	120	300	75	230	200	350	260	180

[1] Each bar represents mean MOR values equivalent at a 95 percent level of significance.

[2] All MOR values are the average of 4 specimens, except for H_2O-air and the untreated controls (CTL), which are the average of 20 specimens each per species. The MOR of untreated aspen controls averaged 7,041 lb/in^2 and that of Douglas-fir controls averaged 6,307 lb/in^2.

Table 6—Results of Tukey's test of means for work to maximum load (WML) of aspen and Douglas-fir plywood after treatment[1,2]

Treatment	R2	Drying temperature											
ASPEN													
BRX	0.651	CTL	140	120	200	250	300	180	260	160	350	230	
NCF	.662	CTL	120	140	250	160	300	350	180	230	200	260	
CZC	.803	CTL	120	140	160	200	180	230	250	350	300	260	
MIN	.601	CTL	140	160	120	250	230	200	260	300	350	180	
PYR	.670	CTL	140	120	160	200	180	230	350	300	250	260	
H_2O	.140	200	250	300	160	CTL	350	140	AIR	260	120	180	230
DOUGLAS-FIR													
BRX	.583	CTL	120	160	140	200	250	350	230	260	180	300	
NCF	.460	CTL	300	250	350	140	160	200	120	180	230	260	
CZC	.604	CTL	140	160	200	120	180	230	260	250	300	350	
MIN	.403	CTL	250	300	180	120	200	140	230	350	160	260	
PYR	.444	CTL	120	140	160	300	260	180	200	230	350	250	
H_2O	.208	AIR	160	CTL	250	120	230	140	300	350	200	260	180

[1] Each bar represents mean MOR values equivalent at a 95 percent level of significance.

[2] All WML values are the average of 4 specimens, except for H_2O-air and the untreated controls (CTL), which are the average of 20 specimens each per species. The WML of untreated aspen controls averaged 960 in-lb and that of Douglas-fir controls averaged 770 in-lb.

Table 7—Results of Tukey's test of means for horizontal (rolling) shear strength (TAU) of aspen and Douglas-fir plywood after treatment[1,2]

Treatment	R^2	Drying temperature										
ASPEN												
BRX	0.369	180	250	200	300	230	CTL	140	120	160	350	260
NCF	.408	300	350	140	250	200	CTL	160	120	260	180	230
CZC	.766	120	CTL	140	180	160	230	200	250	300	260	350
MIN	.319	300	160	350	140	230	CTL	200	250	180	120	260
PYR	.448	350	140	230	300	120	CTL	250	180	160	260	200
H_2O	.930	300	250	140	230	CTL	160	260	200	120	180	350
DOUGLAS-FIR												
BRX	.563	300	CTL	250	180	120	200	160	260	230	140	350
NCF	.609	CTL	140	120	300	250	200	350	180	160	230	260
CZC	.877	CTL	120	140	230	160	200	180	250	260	350	300
MIN	.448	CTL	200	160	300	140	120	250	230	350	260	180
PYR	.579	CTL	120	250	200	180	140	300	230	160	350	260
H_2O	.900	CTL	250	140	300	260	350	120	230	160	180	200

[1] Each bar represents mean TAU values equivalent at a 95 percent level of significance.

[2] All TAU values are the average of 4 specimens, except for untreated controls (CTL), which are the average of 20 specimens each per species. The TAU of untreated aspen controls averaged 278 lb/in^2 and that of Douglas-fir controls averaged 268 lb/in^2.

Table 8—Percent change in three mechanical properties of aspen plywood caused by several treatment and redrying regimes compared to untreated controls

Property	Treatment	Kiln drying								Press drying		
		80	120	140	160	180	200	230	260	250	300	350
		°F								°F		
MOR	H_2O	−19	−13	−12	+2	−15	−7	−7	−5	+3	+1	−8
	BRX	−−	−11	0	−23	−13	+15	−33	−26	−18	−16	−31
	MIN	−−	−8	−1	−2	−34	−29	−32	−46	−22	−31	−40
	PYR	−−	−18	−12	−19	−23	−25	−37	−58	−46	−44	−42
	NCF	−−	+1	−20	−17	−31	−42	−36	−53	−21	−23	−34
	CZC	−−	−30	−37	−37	−52	−57	−59	−87	−80	−90	−88
WML	H_2O	−13	−26	−8	+6	−31	+20	−33	−14	+14	+11	−6
	BRX	−−	−45	−40	−69	−59	−47	−73	−63	−55	−57	−70
	MIN	−−	−34	−20	−29	−69	−60	−56	−64	−54	−64	−68
	PYR	−−	−44	−27	−46	−61	−57	−70	−84	−77	−74	−73
	NCF	−−	−24	−39	−51	−60	−72	−68	−85	−46	−53	−60
	CZC	−−	−41	−56	−59	−80	−74	−83	−98	−92	−97	−96
TAU	H_2O	−−	−7	+12	−1	−7	−6	+8	−2	+13	+15	−15
	BRX	−−	−8	−2	−9	+23	+15	+2	−30	+22	+9	−15
	MIN	−−	−12	+8	+14	−11	−3	+6	−25	−5	+17	+10
	PYR	−−	+8	+19	−6	−4	−24	+11	−9	0	+11	+22
	NCF	−−	−11	+5	−1	−15	+2	−19	−14	+4	+23	+16
	CZC	−−	+12	−4	−13	−9	−31	−26	−60	−36	−45	−78

Table 9—Percent change in three mechanical properties of Douglas-fir plywood caused by several treatment and redrying regimes compared to untreated controls

Property	Treatment	Kiln drying								Press drying		
		80	120	140	160	180	200	230	260	250	300	350
		°F								°F		
MOR	H_2O	-16	-10	-7	+6	-34	-19	-17	-32	-8	-14	-30
	BRX	--	-16	-23	-21	-33	-39	-34	-35	-27	-45	-46
	MIN	--	-16	-27	-24	-8	-15	-25	-33	-6	-14	-39
	PYR	--	-4	-14	-31	-28	-24	-30	-24	-35	-27	-40
	NCF	--	-29	-24	-15	-33	-37	-36	-45	-17	-11	-26
	CZC	--	-26	-21	-30	-31	-34	-41	-49	-59	-77	-80
WML	H_2O	+7	-7	-20	+2	-56	-43	-11	-42	-4	-23	-33
	BRX	--	-40	-64	-50	-70	-58	-68	-70	-59	-73	-65
	MIN	--	-45	-45	-58	-31	-45	-50	-65	-20	-31	-56
	PYR	--	-16	-32	-40	-55	-56	-57	-55	-66	-50	-62
	NCF	--	-52	-35	-36	-59	-51	-64	-75	-30	-24	-30
	CZC	--	-49	-44	-47	-58	-48	-64	-65	-77	-91	-93
TAU	H_2O	--	-15	-1	-16	-27	-32	-16	-12	-1	-8	-13
	BRX	--	-21	-34	-24	-18	-24	-26	-26	-10	+4	-51
	MIN	--	-19	-14	-10	-28	-10	-22	-27	-19	-12	-27
	PYR	--	-9	-17	-26	-17	-17	-23	-47	-11	-19	-26
	NCF	--	-11	-8	-32	-26	-24	-34	-43	-19	-15	-25
	CZC	--	-19	-34	-35	-40	-37	-34	-58	-45	-74	-70

Table 10—Trends exhibited by the three main variables for each species-property combination as interpreted from figures 2-5. For treatment and drying factors the trends are: slightly increasing (+), no difference (=), slightly decreasing (–), and strongly decreasing (–); for species-to- species differences the trends are: no difference (=) and different (*)

Property	Species	Figure reference	Treatment[1]						Drying			Overall species-to-species difference
			H_2O	BRX	MIN	PYR	NCF	CZC	Kiln ≤160 °F	Kiln ≥180 °F	Press	
MOE	Aspen	2	=	+	=	=	=	––	=	=	=	=
	D. Fir	2	=	=	=	=	=	–	=	=	–	
MOR	Aspen	3	=	–	–	–	–	––	–	––	–	=
	D. Fir	3	–	–	–	–	–	–	–	–	–	
WML	Aspen	4	=	––	––	––	––	––	––	––	––	=
	D. Fir	4	–	––	––	––	––	––	––	––	––	
TAU	Aspen	5	=	=	=	=	=	––	=	=	=	*
	D. Fir	5	–	–	–	–	–	––	–	–	=	

[1]Interpreted from both kiln- and press-dried plywood.

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