EFFECTS OF FIRE RETARDANT RETENTION, BORATE BUFFERS, AND REDRYING TEMPERATURE AFTER TREATMENT ON THERMAL-INDUCED DEGRADATION

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ABSTRACT

All wood products are prone to strength loss from extended exposure to temperatures above 65°C (150°F). The higher the temperature, the less time required to produce a given reduction in strength. In the United States, problems with fire-retardant-treated plywood roof sheathing and roof-truss lumber have occurred in the field; thermal degradation has occurred in as few as 2 to 5 years after installation. Before the thermal-induced degradation of treated wood can be fully modeled, we must more completely determine the relationships of treatment processing factors, mixtures of chemical components, post-treatment (redrying) temperature, and in-service moisture to performance, and relate the results to in-service temperature-induced strength degradation. In the study reported here, variation in redrying temperattne from 49°C (120°F) to 88°C (190°F) had little effect on the magnitude or rate of subsequent thermal degradation when the treated plywood was exposed at 65°C (150°F) for up to 290 days. The addition of borate-based buffers to fire-retardant-treatment chemicals was found to significantly mitigate thermal degradation. Finally, the results imply that the combined effects of phosphate retention and accumulated thermal exposure (from both redrying and in-service high temperatures) are additive and cumulative.

T his study evaluated the relative influence of several fire-retardant (FR) chemical, treatment processing, and exposure factors on the structural performance of FR-treated plywood when exposed to a long-term steady-state temperature of 65°C (150°F) and 75 percent relative humidity (RH). The study factors were as follows: 1) varying the mixtures of FR components often used in commercial formulations; 2) varying the redrying temperatures employed in post-FR-treatment kiln-drying; and 3) defining the moisture-related leaching of phosphate from FR-treated material during subsequent rewetting in service. Some of the experimental factors were identified in previous experiments using dynamic mechanical analysis of small veneers (9).

PROBLEM

In-service degradation of FR-treated roof sheathing is caused by thermal-induced acid degradation of wood carbohydrates (12, 18). In previous predictive models for thermal degrade of untreated and FR-treated wood, thermal degrade was found to follow a first-order kinetic relationship (13,15,16,21,22). However, the extent of degradation in mechanical properties and the chemical composition of the wood induced by steady-state laboratory exposures of plywood at 77°C (170°F) and 79 percent RH and solid-sawn wood at 82°C (180°F) and 50 percent RH was far less than the magnitude of degradation often experienced in the field. It has been suggested that the differences between field- and laboratory-induced property degradation rates are related to the severity of the treatment processing factors employed to treat and prepare FR material for field installation (17). The recent development of predictive kinetics-based models has clearly shown that the application of simple first-order kinetic models is not entirely justified (19).

These other processing factors may account for the differences between models based on "first-order" and "best-fit" kinetics. Such processing factors may include the influence of acidity and/or buffering capacities of various FR chemical components used in commercial FR formulations, temperatures employed in kiln-drying FR-treated material after treatment, and/or rewetting of FR-treated plywood during construction. Each factor seems to contribute to the differential performance of laboratory and field materials. However, the relative effect of each factor and their interactions are unknown.

Series	Redry temp.[b]	Fire-retard. treatment[c] MAP/PA/TB	Secondary phase[d]	Time at 66°C/ 75% RH
	(°C)			(days)
1	None	None	Untreated controls	0, 160, 290
2	None	100/0/0	Expose wet with no drying	60, 160, 290
3	49/32[e]	100/0/0	Constant DB throughout	0, 160, 290
4	71/54[f]	100/0/0	Constant DB throughout	0, 60, 160, 290
5	71/54	75/0/25	Constant DB throughout	0, 60, 160, 290
6	71/54	90/10/0	Constant DB throughout	0, 60, 160, 290
7	88/71[g]	100/0/0	Constant DB throughout	0, 60, 160, 290
8	71/54	100/0/0	Rewetted, exposed to field drying	60, 160, 290
9	71/54	100/0/0	Rewetted, exposed without field drying	60, 160, 290

[a] Twenty-four replicate 1/2-inch (12-mm) plywood specimens were used for each redry-exposure combination.
[b] Dry bulb/wet temperature. $t_{°F} = t_{°C} \times 1.8 + 32$.
[c] Weight ratios: MAP = monoammonium phosphate; PA = phosphoric acid; TB = disodium octaborate tetrahydrate (Timbor).
[d] DB is dry bulb temperature.
[e] 48 hours to reach MC of 13 to 16 percent.
[f] 29 hours to reach MC of 20 to 23 percent.
[g] 23 hours to reach MC of 12 to 16 percent.

TABLE 2. — *Experimental design for study of FR mixture effects.*[a]

FR mixture MAP/PA/BA[b]	Redrying temp.[c]	Time at 150°F/ 75% RH
	(°C)	(days)
None	None	0
Water	66/60	0
100/0/0	66/60	0, 290
80/20/0	66/60	0, 160, 290
80/0/20	66/60	0, 160, 290
60/20/20	66/60	0, 160, 290
80/10/10	66/60	0, 160, 290

[a] Twenty replicates of 5/8-inch (12-mm) plywood specimens used for each redry-exposure combination.
[b] Weight ratios: MAP = monoammonium phosphate; PA = phosphoric acid; BA = boric acid.
[c] 43 hours to reach MCs of 20 to 22 percent. Dry bulb/wet bulb temperature. $t_{°F} = t_{°C} \times 1.8 + 32$.

TABLE 3. — *Treatment groups of 1/2-inch plywood specimens.*

Treatment	Specimen groups (n)	Series
Control	1	1
100% MAP	23	2-4, 7-9
75% MAP, 25% Timbor[a]	4	5
90% MAP, 10% phosphoric acid	4	6

[a] Disodium octaborate tetrahydrate.

Background

The general problem of roof sheathing failures in FR-treated plywood has been discussed by the American Plywood Association (3), LeVan and Collet (10), and the National Association of Home Builders (NAHB) (14). Interim guidelines for design were given by Winandy (17) and NAHB (14). The various factors involved in the problem and a proposed thermo-chemical mechanism were presented by LeVan and Winandy (11). Some factors discussed in that report are the historical precedence for redrying temperature limits and the effects of the temperatures used to kiln-dry FR-treated lumber and plywood after treatment. The report reviews work by many investigators (5,7,8,20), which consistently showed that post-treatment redrying temperatures were critical to the magnitude of initial FR-treatment-induced strength loss. This research on post-treatment redrying temperatures provided the basis for the redrying temperature limits of 71°C (160°F) for FR material intended for use at or near room temperature in AWPA Standards C-20 and C-27 (4). A review of the literature and our recent research results revealed that the effect of redrying temperature on the in-service performance of FR-treated plywood roof sheathing at elevated temperatures is unknown.

Moisture content (MC) is known to exaggerate the immediate effects of elevated temperature on the strength of untreated wood; the relationship of MC to permanent effects is similar but less documented (6). It is reasonable to assume that higher MC could also magnify the thermal degradation of FR-treated material. However, the effects of MC on in-service performance of FR-treated plywood roof sheathing were examined only recently (3,21) and much is still unknown. Such information is vital to developing a service-life model because it may explain the differential performance between laboratory results and field experience.

Commercial FR formulations are mixtures of chemicals that provide varying degrees of tire resistance to wood. The potential of several FR chemicals to accelerate thermal degrade is documented (12), but potential chemical interactions between FR mixtures and their influence on the thermal degradation of treated plywood are undocumented. Such information would greatly increase the adaptability and accuracy of the ensuing service-life model currently under development at the Forest Products Laboratory (FPL) to adjust for changes in FR formulations.

EXPERIMENTAL PROCEDURES

CUTTING

Two thicknesses of southern pine plywood were used for the study: 1) 1/2-inch- (12-mm-) thick plywood, 24 four-ply sheets, N-grade veneer (special grade used in previous FPL studies to reduce variability in mechanical properties resulting from random defects in interior veneers); and 2) 5/8-inch- (16-mm-) thick plywood, 20 five-ply, N-grade veneer. From each 4- by 8-foot (1.22- by 2.44-m) sheet, thirty-two 6-inch- (152-mm-) wide by 24-inch- (610-mm-) long (parallel to face grain) specimens were cut.

SORTING

One specimen from each sheet of 1/2-inch plywood was randomly assigned to 32 experimental groups (**Table 1**), and one specimen from each sheet of 5/8-inch plywood was randomly assigned to 20 experimental groups (**Table 2**). This blocked experimental design was chosen because it allowed within-panel error (i.e., variability) to be separated from between-panel error in analysis of variance. Twenty-four specimens per group allowed the mean values of each group to be estimated with 75 percent confidence when assuming a 20 percent coefficient of variation in mechanical properties (l).

TREATMENT

1/2-inch plywood. — Treatment groups are described in **Table 3.** Specimens treated with monoammonium phosphate (MAP) served as a model of

an inexpensive, inorganic FR. Specimens treated with a combination of MAP and disodium octaborate tetrahydrate (Timbor®) served as a model for a buffered inorganic FR formulation. Specimens treated with a combination of MAP and phosphoric acid served as a model for a lower quality, highly acidic, inorganic FR formulation.

All FR treatments were full-cell with an initial vacuum of 92 kPa (27 inHg) for 30 minutes, pressure of 1.03 MPa (150 psi) for 1 hour, and no final vacuum. Gross absorption averaged 480 kg/m^3 (30 pcf), and individual treatment solutions were set accordingly to achieve a target retention of 56 kg/m^3 (3.5 pcf a.i.).

Each plywood group was either not dried or kiln-dried after treatment (**Table 1**). The kiln-dried material was equilibrated at 23°C (74°F) and 65 percent RI-I

to an approximate equilibrium MC (EMC) of 12 percent for untreated material before exposure. Material that was not kiln-dried after treatment or material that was kiln-redried and then rewetted was exposed in a 65°C (150°F) chamber in the wet condition and allowed to dry (and thereby leach out the waterborne FR chemical) during high-temperature exposure. No attempt was made to maintain the wet condition in these specimens.

5/8-inch plywood. — Treatment groups are described in **Table 4.** Specimens treated with a combination of 80 percent MAP and 20 percent boric acid served as a model for buffered inorganic FR formulations; those treated with 80 percent MAP and 20 percent phosphoric acid served as a model for an acidified inorganic formulation. The 80 percent MAP + 10 percent phosphoric acid + 10

percent boric acid solution and the 60 percent MAP + 20 percent phosphoric acid + 20 percent boric acid solution served as models for both acidified and buffered inorganic FR formulations.

Each group was kiln-dried after treatment, as described in **Table 2.** All un-

TABLE 4. — *Treatment groups of 5/8-inch plywood specimens.*

Treatment	Specimen groups (*n*)
Untreated control	1
Water-treated control	1
100% MAP	2
80% MAP, 20% boric acid	3
80% MAP, 20% phosphoric acid	3
60% MAP, 20% phosphoric acid, 20% boric acid	3
80% MAP, 10% phosphoric acid, 10% boric acid	3

TABLE 5. — *Mechanical properties of 1/2-inch (12-mm) plywood under various treatment and exposure conditions.*[a]

Series	Treatment	Redry	Exp.	MOE Mean	MOE SD	MOR Mean	MOR SD	WML Mean	WML SD
		°C (°F)	(days)	- - - - - - (GPa) - - - - - -		- - - - - - (MPa) - - - - - -		- - - - - - (kJ/m^3) - - - - - -	
1	Untreated	None	0	11.70	1.79	71.8	11.4	39.9	16.1
			60	11.56	2.05	69.5	11.9	33.3	9.6
			160	9.92	2.02	58.3	10.8	34.2	20.0
			290	11.54	1.83	55.2	10.3	22.4	10.4
2	100% MAP	None/dry[b]	60	9.35	1.40	43.8	6.3	19.9	7.1
			160	9.02	1.83	38.6	5.9	13.1	5.1
			290	9.10	1.76	26.0	7.6	5.5	3.4
3	100% MAP	49 (120)	0	10.90	2.59	58.9	8.8	29.7	10.5
			60	- -	- -	- -	- -	- -	- -
			160	8.52	2.15	28.5	7.0	6.7	3.6
			290	7.61	1.61	17.4	4.9	2.5	1.5
4	100% MAP	71 (160)	0	10.32	2.35	57.4	10.2	31.6	10.4
			60	9.23	2.23	36.3	8.8	11.3	5.3
			160	8.62	1.75	25.8	7.5	5.2	2.9
			290	7.68	2.05	17.1	5.2	2.4	1.2
5	75% MAP/25% TB	71 (160)	0	10.83	1.58	59.6	9.3	29.2	11.4
			60	9.67	1.83	42.4	9.8	14.7	6.9
			160	8.87	2.02	34.7	8.9	9.9	5.6
			290	9.45	1.95	25.8	6.1	4.9	2.6
6	90% MAP/10% PA	71 (160)	0	11.05	2.04	57.5	7.1	28.4	9.0
			60	9.48	2.12	36.6	9.1	10.5	5.4
			160	8.49	1.59	26.4	6.9	5.5	2.5
			290	7.45	1.78	17.6	4.3	2.7	1.2
7	100% MAP	88 (190)	0	10.21	2.00	51.5	9.5	25.0	12.1
			60	9.21	2.52	35.6	10.6	10.3	5.7
			160	8.05	1.65	23.5	5.4	4.5	1.9
			290	7.90	1.60	17.0	4.0	2.4	1.1
8	100% MAP	71/rewet/dry[b]	60	9.34	1.94	44.5	6.0	18.5	8.0
			160	8.07	1.89	31.5	8.5	10.2	5.8
			290	9.36	2.10	32.9	6.0	10.5	4.8
9	100% MAP	71/rewet/no dry[c]	60	9.42	2.17	43.8	8.8	17.2	7.6
			160	8.94	1.86	36.6	8.1	12.1	6.3
			290	8.52	1.94	26.4	5.7	6.3	3.0

[a] TB = Timbor; SD = standard deviation. 1 psi = 6.894 kPa; 1 in.-lb./in.^{3} = 6.894 1 kJ/m^3.
[b] Installed in high-temperature chamber while wet, but allowed to dry during exposure.
[c] Installed in high-temperature chamber while wet, but inhibited from drying during exposure.

TABLE 6. — Mechanical properties of 5/8-inch (16-mm) plywood under various treatment and exposure conditions.[a]

Treatment % MAP/PA/BA[b]	Exp.	MOE Mean	MOE SD	MOR Mean	MOR SD	WML Mean	WML SD
	(days)	--------- (GPa) ---------		--------- (MPa) ---------		--------- (kJ/m^3) ---------	
100/00/00	0	10.18	1.37	55.0	10.1	12.5	7.6
	160	- -	- -	- -	- -	- -	- -
	290	7.39	1.22	14.6	3.5	2.0	0.7
80/20/00	0	10.38	1.34	53.9	8.3	25.0	9.4
	160	8.69	0.99	26.1	6.2	5.2	2.5
	290	8.29	0.96	16.4	4.0	2.3	1.1
80/00/20	0	10.47	1.13	56.3	8.8	23.7	9.4
	160	8.50	1.06	27.2	4.6	6.1	2.1
	290	8.61	1.13	19.0	4.0	3.0	0.8
60/20/20	0	9.54	1.22	54.7	9.0	23.2	9.9
	160	8.52	1.21	28.4	5.6	6.9	3.0
	290	8.59	1.24	21.0	5.3	3.4	1.6
80/10/10	0	9.97	1.77	58.5	6.4	29.4	9.8
	160	8.70	1.06	27.1	5.6	5.7	2.4
	290	8.53	1.05	18.9	4.7	3.0	1.1
Water	0	9.94	1.46	62.7	8.0	34.8	15.1
Untreated	0	10.45	1.35	68.0	11.9	40.5	25.6

[a] Dry bulb/wet bulb redry temperature was 66°C/60°C (150°F/140°F).
[b] PA = phosphoric acid; BA = boric acid.

treated kiln-dried material was equilibrated at 23°C (74°F) and 65 percent RH to approximately 12 percent EMC before high-temperature exposure.

HIGH-TEMPERATURE EXPOSURE

Selected groups of plywood were placed in a controlled environmental chamber and held at 65°C (150°F) and 75 percent RH for predetermined times (**Tables 1** and **2**). As was done after redrying, all material was re-equilibrated to 23°C (74°F) and 65 percent RH after the appropriate exposure at 65°C (150°F).

MECHANICAL TESTING

Each 150- by 610-mm (6-by 24-in.) plywood specimen was tested in bending using the center-point load configuration of ASTM D 3047 (2), but only load and center-span deflection were recorded. Maximum bending moment, stiffness, modulus of elasticity (MOE), modulus of rupture (MOR), and work to maximum load (WML) were calculated.

RESULTS AND DISCUSSION

Mechanical properties of 1/2-inch and 5/8-inch plywood specimens are shown in **Tables 5** and **6,** respectively. Results of elemental phosphorus analysis of FR-treated plywood after extended exposure at 66°C (150°F) using x-ray fluorescence spectrometry are given in **Table 7.**

EFFECTS OF KILN-DRYING AFTER TREATMENT

The effects of various post-treatment kiln-drying temperatures and their sub-

TABLE 7. — Retention of elemental phosphorus using x-ray fluorescence spectrometry.

Series	Treatment/KDAT/Rewet[a]	Retention at various exposure times (days)[b]			
		0	60	160	290
		-------------- (wt. %) --------------			
1	Untreated control	0.10	- -	- -	0.08
2	100% MAP/None/None	- -	1.76	2.47	2.20
4	100% MAP/71°C/None	1.92	2.26	- -	2.07
5	75% MAP + 25% TB/71°C/None	1.41	1.45	- -	1.59
6	90% MAP + 10% TB/71°C/None	2.13	2.45	- -	2.48
8	100% MAP/71°C/Leached	- -	1.52	- -	1.44

[a] KDAT = kiln-dried after treatment (temp.); 71°C = 160°F; TB = Timbor.
[b] Exposure temperature was 66°C (150°F).

sequent effect on high-temperature thermal degradation can be seen by comparing the three 100 percent MAP-treated groups that were redried at either 49°C (120°F), 71°C (160°F), or 88°C (190°F), and the untreated controls (**Table 5, Fig. 1).** The magnitude of initial (after post-treatment redrying but prior to steady-state exposure at 66°C (150°F)) losses in bending strength was nearly identical for FR-treated plywood redried at 49°C (120°F) and material redried at 71°C (160°F). Further, note that while the effect of redrying at 88°C (190°F) appears slightly greater, the difference in initial bending strength was not significant ($p <$ 0.05). Finally, note that the initial effect of the redrying process at several temperatures is consistent with previous findings (5,7,20) in that the approximately 10 to 20 percent loss in initial

bending strength can be directly attributed to FR treatment and redrying.

Any small differences in bending strength related to post-treatment redrying temperature all but disappeared after 290 days of steady-state exposure at 66°C (150°F) (**Fig. 1).** This exposure reduced the initial bending strength of the FR-treated plywood by roughly another 65 percent, regardless of redrying temperature. There were no significant ($p <$ 0.05) differences in rate of thermal degrade of bending strength among the three redrying temperatures studied (**Fig. 1).** Thus, there appears to be little relationship between the severity of the post-treatment kiln-drying temperature and the susceptibility of the kiln-dried material to experiencing thermal degrade upon in-service exposure to high temperatures (**Fig. 1).** For WML, the thermal degrade-effects relationship with respect
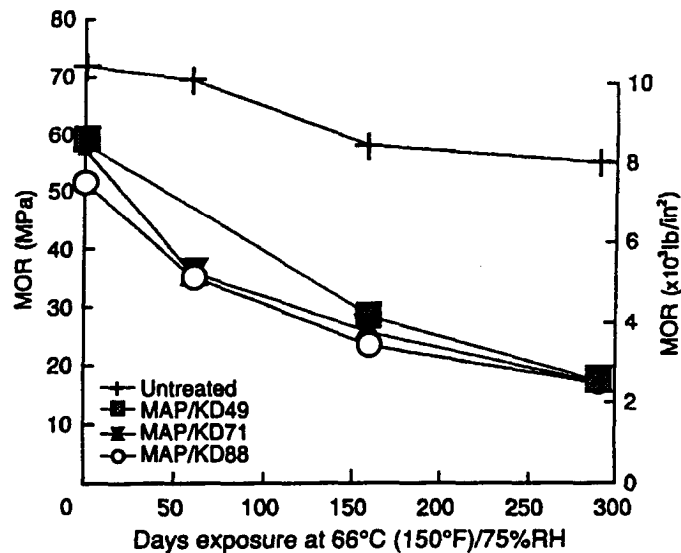
Figure 1. — Effect of redrying temperatures on bending strength of 1/2-inch (12-mm) monoammonium phosphate (MAP)-treated plywood. KD is kiln redrying temperature in °C.
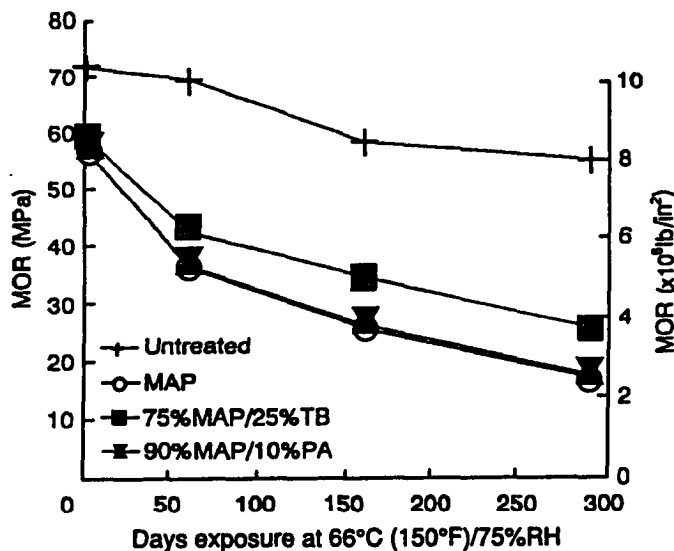

Figure 2. — Effect of FR mixtures on bending strength of 1/2-inch (12-mm) plywood. TB = Timbor; PA = phosphoric acid.

TABLE 8. — Results of blocked analysis of variance on effects of FR mixtures on mechanical properties of 1/2-inch (12-mm) plywood after extended high temperature exposure.[a]

Property	Exposure (days)	Groups[b]			
MOE	0	Unt	MP	MB	M
			MB	MP	M
	160	Unt	MB	M	MP
	290	Unt	MB	M	MP
MOR	0	Unt	MB	MP	M
			MB	MP	M
	160	Unt	MB	MP	M
	290	Unt	MB	MP	M
WML	0	Unt	M	MB	MP
	60		MB	M	MP
	160	Unt	MB	MP	M
	290	Unt	MB	MP	M

[a] High temperature exposure of 66°C (150°F).
[b] Group designations: Unt = untreated control (series 1); M = monoammonium phosphate (MAP) (series 4); MP = MAP + phosphoric acid (series 6); MB = MAP + Timbor (series 5). Lines indicate statistically equivalent group means ($p \leq 0.05$).

towards accelerating in-service thermal degrade.

EFFECTS OF FIRE RETARDANT MIXTURES

The effects of various mixtures of potential FR chemicals were evaluated for 1/2-inch and 5/8-inch plywood. Although the specific objectives of these substudies were different, the overall conclusions from each substudy eventually supported the same conclusion. Each size of plywood will be discussed separately.

For 1/2-inch-thick plywood, the objective was to evaluate the effect of adding borate (as disodium octaborate tetrahydrate) to plywood treated with various mixtures of FR chemicals and then subsequently exposed to high temperatures. The mitigating influence of borate on thermal degradation can be seen by comparing the untreated control group to the groups treated with 100 percent MAP, 75 percent MAP + 25 percent Timbor, and 90 percent MAP + 10 percent phosphoric acid (**Table 5, Fig. 2**).

The addition of borate to the FR mixture had no significant effect on mitigating the susceptibility of MOE or WML to subsequent thermal degradation when the wood was exposed to high tempera-

to redrying temperature was similar to that for bending strength. For MOE, the relationship was even less apparent than that for bending strength.

Accordingly, in a hypothetical case of a treater exceeding the redrying temperature limit of 71°C (160°F) imposed in AWPA Standards (4) by 10°C (18°F), there might be a greater initial loss in plywood strength. However, there would seem to be no reason to expect excessive redrying temperatures of up to 20°C (36°F) above AWPA limits to have a significant differential effect on the rate

of in-service thermal degrade. Thus, redrying temperatures between 49°C (120°F) and 88°C (190°F) are not expected to raise the susceptibility of FR-treated and redried material to thermal degrade. This finding is probably related to the fact that the higher redrying temperatures required a shorter duration of thermal exposure (**Table 1**). However, use of redrying temperatures higher than 88°C (190°F) has not been extensively studied and should conservatively be expected to cause some additional cumulative effect
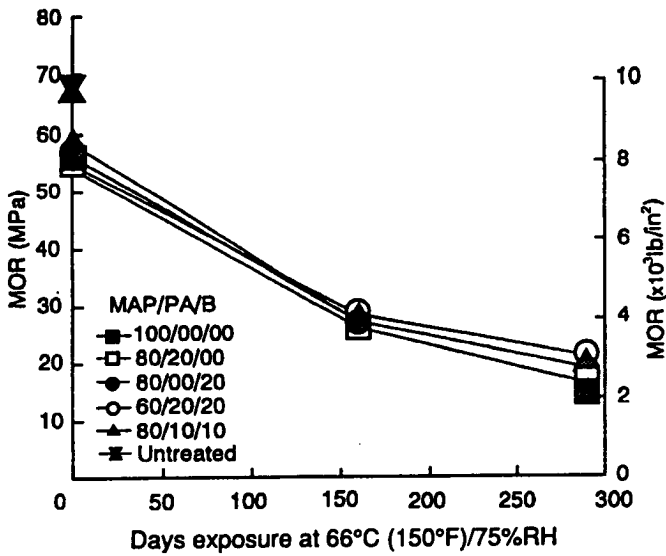
Figure 3. — Effect of various percentages of FR mixtures on bending strength of 5/8-inch (16-mm) plywood. PA = phosphoric acid; B = boric acid.

TABLE 9. — Results of blocked analysis of variance on effects of FR mixtures on mechanical properties of 5/8-inch (16-mm) plywood after extended high temperature exposure.[a]

Property	Exposure	Groups[b]						
	(days)							
MOE	0	80/0/20	Unt	80/20/0	100/0/0	80/10/10	Water	60/20/20
	160	80/10/10	80/20/0	60/20/20	80/0/20			
	290	80/0/20	60/20/20	80/10/10	80/20/0	100/0/0		
MOR	0	Unt	Water	80/10/10	80/0/20	100/0/0	60/20/20	80/20/0
	160	60/20/20	80/0/20	80/10/10	80/20/0		•	
	290	60/20/20	80/0/20	80/10/10	80/20/0	100/0/0		
WML	0	Unt	Water	80/10/10	100/0/0	80/20/0	80/0/20	60/20/20
	160	60/20/20	80/0/20	80/10/10	80/20/0			
	290	60/20/20	80/0/20	80/10/10	80/20/0	100/0/0		

[a] High temperature exposure of 66°C (150°F).
[b] Group designations: X/Y/Z ratio indicates percentage (by weight) of MAP/phosphoric acid/Timbor; Unt = untreated control; water = water-treated control. Lines indicate statistically equivalent group means ($p = \leq 0.05$).

tures (**Table 8**). However, the addition of borate benefited MOR significantly (**Table 8**). This effect was especially noticeable after the 160- and 290-day exposures (**Fig. 2**). Note that the magnitude of differences in bending strength between borate- and nonborate-containing mixtures of FR-treated plywood were only marginally different at day 0 (i.e., no in-service exposure); on extended exposure (160 and 290 days), the mitigating effect of adding borate became apparent. However, while it appears that adding borate lessened the magnitude of thermal degrade, there were no significant differ-

ences between the rates of thermal degrade for borate- and nonborate- supplemented FR treatments.

For 5/8-inch-thick plywood, the objective was to evaluate the mitigating effect on thermal degrade of increasing proportions of borate (this time as boric acid) and of increasing proportions of acid (as phosphoric acid) to plywood treated primarily with MAP and then exposed to high temperatures. The influences of boric acid and/or phosphoric acid on thermal degradation can be seen by comparing the untreated control to groups treated with 100 percent MAP, 80

percent MAP + 20 percent boric acid, 80 percent MAP + 20 percent phosphoric acid, 80 percent MAP + 10 percent boric acid + 10 percent phosphoric acid. and 60 percent MAP + 20 percent boric acid + 20 percent phosphoric acid (**Table 6, Fig. 3**).

For MOE, few real benefits were apparently derived from adding borate to the FR mixture (**Table 9**). However, after 290 days of exposure the borate supplement caused significant benefits for MOR and WML (**Table 9**). This mitigating influence of borate (as boric acid) on thermal degrade was significant, but less readily apparent with the 5/8-inch plywood (**Fig. 3**) than with the 1/2-inch plywood (**Fig. 2**).

EFFECTS OF RETENTION

The actual process used for rewetting previously FR-treated and kiln-dried plywood specimens (i.e., retreating with water at about 50% of pressure used in FR treatment) caused a notable reduction in phosphate retention (**Table 7**). Thus, the intended objective of this phase of the study, which was to evaluate the influence of in-service MC and rewetting on the thermal degrade of FR-treated plywood, was confounded by the leaching of phosphate.

Although these data cannot be used to address the effects of in-service MC, they do provide some important information on the relationship between phosphate retention and thermal degrade. Recalling that the rewetting process effectively caused phosphate chemical to be leached from the FR-treated plywood, the statistical analysis of the strength results (**Fig. 4, Table 10**) showed that chemical leaching of phosphate diminished the amount of thermal degrade when compared to degrade of similarly treated FR-treated plywood that was unleached and had higher phosphate retention (**Table 7**).

Finally, the effect of the relationship between FR retention and cumulative thermal loading (i.e., thermal load history including redrying after treatment and subsequent exposures to elevated in-service temperatures) on the rate and magnitude of thermal degrade can be addressed with these data. These relationships can be addressed by comparing variously treated/leached and re-dried/thermally exposed groups. Recall that as a result of phosphate leaching, some groups of FR-treated plywood had high phosphorus retention of about 2 per-

cent (range = 1.76% to 2.47%), and because they were redried they had higher cumulative thermal loading. Others had high phosphorus retention, but were never redried (i.e., so these groups had reduced cumulative thermal loading). Still other groups were kiln-redried, rewetted, and leached, so they had lower initial phosphorus retention of about 1.5 percent (1.44% to 1.52%) (**Table 7**) and higher cumulative thermal loading.

The results shown in **Table 10** indicate that the higher retention/higher cumulative thermal loaded group (MKD) was the most significantly reduced in strength and WML, and, to a lesser extent, MOE (**Fig. 4, Table 5**). Further, the higher retention/lower cumulative thermal loaded group and the lower retention/higher cumulative thermal loaded group experienced statistically comparable levels of thermal degrade (**Fig. 4,** MNW and MKW groups, respectively). If cumulative thermal exposure is defined as the entire thermal history through both redrying after treatment and in-service high temperatures, then these data support the hypothesis that the effects of phosphate retention and cumulative thermal exposure are both additive and cumulative. Note that the lower retention material, which was redried after treatment and therefore exposed to greater cumulative thermal loading, experienced thermal degrade nearly identical to that of the higher retention material, which was never redried (**Fig. 4**). This trend was noted for MOR, WML, and, to a lesser extent, MOE (**Table 10**).

CONCLUSIONS

A comparison of FR-treated plywood redried after treatment at various temperatures between 54°C (120°F) and 88°C (190°F), revealed no significantly different effects in the magnitude or rate of subsequent susceptibility of those materials to in-service thermal degrade. This result was probably related to the fact that the higher redrying temperatures required a shorter duration of thermal exposure. However, the use of redrying temperatures substantially higher than 88°C (190°F) was not studied. Such redrying temperatures might conservatively be expected to impart some additional cumulative effect toward accelerating in-service thermal degrade.

The addition of borate buffers to phosphate-based FR-treatment chemicals at a phosphate-to-borate ratio be-

Figure 4. — Effects of FR retention, rewetting, and leaching on bending strength of 1/2-inch (12-mm) plywood.

TABLE 10. — *Results of blocked analysis of variance on effects of in-service moisture content on mechanical properties of FR-treated 1/2-inch (12-mm) plywood after extended high temperature exposure.*[a]

Property	Exposure	Groups[b]			
MOE	0		$\overline{\text{Unt}}$	$\overline{\text{MKD}}$	
	60		$\overline{\text{MKW}}$	$\overline{\text{MNW}}$	$\overline{\text{MKD}}$
	160	$\overline{\text{Unt}}$	$\overline{\text{MNW}}$	$\overline{\text{MKD}}$	$\overline{\text{MKW}}$
	290	$\overline{\text{Unt}}$	$\overline{\text{MNW}}$	$\overline{\text{MKW}}$	$\overline{\text{MKD}}$
MOR	0		$\overline{\text{Unt}}$	$\overline{\text{MKD}}$	
	60		$\overline{\text{MKW}}$	$\overline{\text{MNW}}$	$\overline{\text{MKD}}$
	160	$\overline{\text{Unt}}$	$\overline{\text{MNW}}$	$\overline{\text{MKW}}$	$\overline{\text{MKD}}$
	290	$\overline{\text{Unt}}$	$\overline{\text{MKW}}$	$\overline{\text{MNW}}$	$\overline{\text{MKD}}$
WML	0		$\overline{\text{Unt}}$	$\overline{\text{MKD}}$	
	60		$\overline{\text{MNW}}$	$\overline{\text{MKW}}$	$\overline{\text{MKD}}$
	160	$\overline{\text{Unt}}$	$\overline{\text{MNW}}$	$\overline{\text{MKW}}$	$\overline{\text{MKD}}$
	290	$\overline{\text{Unt}}$	$\overline{\text{MKW}}$	$\overline{\text{MNW}}$	$\overline{\text{MKD}}$

[a] High temperature exposure of 66°C (150°F).
[b] Group designations: Unt = untreated control (series 1); MKD = MAP-treated, kiln-redried, and exposed dry (~12% MC) (series 4); MKW = MAP-treated, kiln-redried, rewetted, exposed wet ($\geq$ 30% MC) with leaching (series 8 and 9); MNW = MAP-treated, no redrying, and exposed wet ($\geq$ 30% MC) (series 2). Lines indicate stastistically equivalent group means ($p \leq 0.05$).

tween 3:1 and 4:1 seemed to significantly mitigate subsequent thermal degrade when FR-treated plywood was exposed to elevated in-service temperature. From a qualitative basis, it did not matter whether borate was in the form of disodium octaborate tetrahydrate (Timbor) or boric acid.

Finally, the results show that phosphate-treated plywood exposed to a lower cumulative thermal exposure or having reduced phosphate retention experienced less thermal degradation than did material having higher phosphate re-

tention or higher cumulative thermal loading. These results support a hypothesis that the combined effects of phosphate retention and cumulative thermal exposure are both additive and cumulative.

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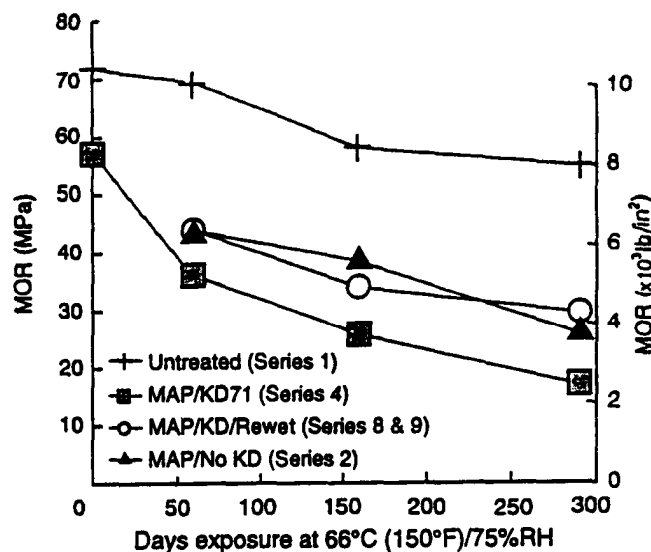
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