LABORATORY AND FIELD EXPOSURES OF FRT PLYWOOD: PART 2—MECHANICAL PROPERTIES[1]

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Abstract. Our understanding of how to interpret the laboratory-induced degradation data to real-world in-service performance of fire-retardant (FR) systems is currently limited because we are unable to correlate laboratory steady-state experiments with actual in-service field performance. Current model studies have generally been limited to isothermal rate studies with selected model FR chemicals. Other factors also play a major role in the degradation of FR-treated wood. These factors, which have not been studied in any detail, include RH/MC cycles and thermally induced evolution of ammonia from ammonium phosphates to provide phosphoric acid. Because there exists no known direct comparison of matched samples with one exposed to high-temperature laboratory conditions and the other exposed for an extended period of time as traditionally used in North American light-framed construction, the objective of this study was to determine the relationship for FR model compounds between laboratory and field results based on strength–temperature–RH (MC)–FR chemical interactions. The impact of the variables was evaluated by measuring bending strength properties and comparing matched laboratory and field exposure samples. The physical test data show the positive effects of adding a buffering system to model FR compounds when exposed to high moisture environments and the negative effects of increasing the moisture in the in-service environment during exposure.

Keywords: Fire retardants, strength, moisture, buffer.

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INTRODUCTION

In the late 1980s and early 1990s, the degradation of wood treated with fire-retardant (FR) chemicals in roof systems was a problem of major national significance with millions of dollars

in litigation and roof replacement being spent. Eventually, laboratory steady-state accelerated procedures using high temperatures and humidity were developed to "screen" fire-retardant formulations before commercial use. However, our understanding of laboratory-induced degradation is currently limited because we are unable to correlate laboratory steady-state experiments with actual in-service field degradation.

Fire retardants were first used in this country by the US Navy in 1895 (Moreell 1939). Preliminary research (Prince 1914; Hunt et al 1930, 1931, 1932; Truax et al 1933, 1935) led to the use of combinations of ammonium sulfate, diammonium phosphate, borax, and boric acid as commercial fire retardants. Materials treated with these systems have been used successfully in structures at or near room temperature for more than 60 yr. A short history of FR-treated wood and its acceptance by building codes can be found in the literature (Catchpole 1976). Overviews of FR-treated wood use in the US are available (Barnes 1993, 1994).

In the 1970s, concern over hygroscopicity and subsequent fastener corrosion led the industry to develop new FR systems with lower hygroscopicity and corrosion potential, known generically as second-generation fire retardants (Davies 1979). These systems entered the marketplace in the early 1980s.

Much debate, but little reliable data, still exists as to the relative influence of various material, construction, and treatment chemical and processing factors, each of which may or may not have played a role in the performance of fire-retardant treated (FRT) panel products through the 1980s. A new use was developed in that there was a change in the model building codes that allowed the use of FR-treated plywood sheathing as a replacement for noncombustible deck and parapet wall systems in multifamily structures. The product standards for panels were revised in 1980 and these changes may have affected panel properties (Anon 2007). Because of the energy crisis, construction practices also changed to provide more resistance to passive air infiltration and these new structures relied more on designed-in passive ventilation or even active mechanical ventilation. At the same time, structures were better insulated in an attempt to make them more thermally efficient. This also had the potential for increasing the in-service temperatures and probably the moisture loads to which wooden roofing members were exposed. There were also questions regarding the treating and kiln-drying practices used to produce the FR-treated plywood.

Before the advent of second-generation systems, the National Design Standard (NDS) for Wood Construction (NFoPA 1977) required a 10% reduction in allowable unit stresses for lumber treated with fire retardants to account for treatment/drying effects. Similarly, for the first-generation systems, the Plywood Design Specification (PDS) required a 16.7% (1/6th) reduction in allowable stresses and a 10% reduction in modulus of elasticity (APA 1965). Owing in large part to substantial differences among second-generation systems, the 1982 NDS was amended in 1984 to require users to obtain changes in design values from FR producers. A proposal for code change requiring formulation-specific design values was accepted in 1986 (ICBO 1986). Since then, adjustments ranging from 10 – 20% (depending on the design stress involved) have been based on first a NFoPA protocol (NFoPA 1986) and then ASTM test methods (ASTM 2008a, 2008b, 2008c, 2008d). Later, NFoPA and the American Plywood Association (APA) removed stress reductions for FR-treated plywood and recommended that users obtain reduction factors from individual companies (APA 1985).

Concern over strength and property losses in FR-treated plywood decking in the field began to emerge in the late 1980s (APA 1987a, 1987b, 1987c, 1989; LeVan and Collet 1989; NAHB 1990). Heretofore, concerns over strength loss had focused on reductions resulting from the redrying of treated wood and plywood (Brazier and Laidlaw 1974; Adams et al 1979). This concern was manifested in American Wood-Preservers' Association (AWPA) Standards C20

and C27, which limited redrying temperature to 71°C so long as the MC was above 25% (AWPA 1985a, 1985b). In 1987, an NFoPA taskforce was formed to investigate the allegations that in-service thermal degradation of FR-treated plywood roof sheathing was occurring. After deliberations, the taskforce recommended that: 1) the 71°C redrying limit be strictly adhered to; 2) FR treated wood be kept dry after redrying and during subsequent storage, handling, and installation; and 3) research be conducted to investigate the influence of the in-service thermal environment on FR-treated plywood (NFoPA 1987).

A survey of the pertinent literature (Winandy et al 1988; LeVan and Winandy 1990) indicated that the published recommendations for initial reductions in modulus of rupture (MOR) for wood (10%) and plywood (17%) were appropriate, a conclusion reached earlier by Gerhards (1970) in his review of 25 yr of unpublished work done at the USDA Forest Products Laboratory. Winandy et al (1988) indicated that redrying plywood treated with model FR systems at or below 71°C had effects comparable to those reported in the literature but that drying at elevated temperatures greatly reduced strength and energy-related property values. Their results, taken with those of MacLean (1945, 1951, 1953) with untreated wood, led to their recommendation that prolonged exposure of FR-treated wood to temperatures greater than 66°C should be avoided. The NDS (NFoPA 1986) also recognized this prohibition by requiring adjustments to design values for exposures in excess of 66°C. Although there were a few conflicting views (eg Brazier and Laidlaw 1974), Eickner's (1966) comment that "there is no evidence that wood treated with the fire-retardant chemicals will undergo further deterioration on aging at normal exposure conditions" characterizes the consensus opinion held until the mid-1980s.

Since that time, a relatively large database of steady-state laboratory exposure to elevated temperatures has been developed by the US FPL and others (Winandy et al 2000; Wang et al 2005). The work with plywood (Winandy et al 1991b) led to the ASTM Emergency Standard ES-20 (ASTM 1992), which was promulgated into ASTM D 5516 in 1995. Other than the initial strength loss from treatment and redrying, no further reductions in strength were noted after extended exposure at temperatures up to 54°C. The steady-state exposure data for both plywood (Winandy et al 1991a) and lumber (LeVan and Winandy 1990) indicate the initial reduction in strength (the magnitude of which was a function of the FR chemical used) was followed by a mostly linear decrease in strength over time of exposure at an elevated temperature of 82°C. Extensive subsequent work at 66°C found intermediate effects between 54 and 82°C (Winandy and Beaumont 1995; Winandy and Lebow 1996; Lebow and Winandy 1999). In all cases, the magnitude of the differences was attributable to the FR treatment used and the temperature condition. After initial effects were accounted for, the rate of change appeared to be independent of the treatment with both untreated and treated samples yielding similar degradation rates. Because of this, the authors concluded that differences among FR systems relative to in-service performance were related to the initial time required for the chemical to dissociate at some temperature into its acidic chemical form. Based on chemical analyses, the authors (LeVan and Winandy 1990) postulated that breakdown of the hemicellulose fraction in wood is primarily responsible for the strength losses encountered.

Unfortunately, the effect of MC, other than at 12% MC, is not well defined in these or other studies. For both elevated temperature studies (LeVan and Winandy 1990; Winandy et al 1991b), the authors concluded that, within the RH limits studied, temperature appeared to be the overriding effect. In an attempt to elucidate moisture effects, LeVan et al (1995) conducted a cyclic exposure study in which temperature was varied daily between 27 and 66°C at either 6 or 12% MC in untreated wood. Exposure time varied from 215 da for the 6% to 400 da for the 12% samples. The authors concluded that cyclic temperature exposures had minimal effect on

strength properties up to 400 da of exposure. Strength values of materials exposed to those cyclic temperatures at 12% MC were slightly, but not significantly, lower than those at 6%, leading the authors to conclude that no difference existed from high temperature exposure over 6 – 12% MC. In another study using dynamic mechanical analysis, LeVan (1993) found that MC was a critical component, more so than temperature or time at temperature, but application/interpretation in this study was partially limited by problems with grip slippage in the DMA machine.

Hodgins and Lee (2002) reported that mechanical properties of FR-treated lumber were reduced compared with those of untreated lumber. However, subsequent questions regarding the preparation and testing of the specimens and the differences in exposure conditions between the treated and untreated samples cloud the validity of this report.

The foregoing background indicates that there still is not a definitive understanding of all factors affecting the in-service performance of FR-treated wood and plywood. In particular, the interaction and duration effects of temperature/RH in-service, especially at wood MC >12%, have not been defined. The ASTM protocol developed for evaluating sheathing materials is not a service-oriented test (Winandy et al 1991b; ASTM 1992). Although data obtained using this protocol are useful, they do little to define the actual mechanism or fully replicate the degradation sometimes observed in the field. For example, taking the data from the test protocol for samples after laboratory exposure for 63 da at 77°C (Winandy et al 1991b), one can calculate losses in MOR of 31.1% for the untreated and 47.7% for the treated samples. The difference in strength loss is approximately 16.6%, a value equal to the reduction in the PDS (APA 1985) previously cited.

One must conclude that factors other than temperature led to the differences between laboratory tests and the observations seen in actual field exposure. One factor might have been the difference between the evaluation of model FR compounds such as monoammonium phosphate (MAP) and commercially formulated products containing multiple compounds, including buffers. Another might have been the influence of construction practices like roof slope, ventilation, vapor barriers, roof color, rewetting during construction, and the storage and handling of treated material after treatment and redrying that would also affect serviceability. Still other possible factors affecting serviceability were the treating and kiln-drying practices used in the preparation of the treated products. Generally, the laboratory strength studies were done under conditions that mimicked standardized commercial practices, but it was possible that treaters used more extreme conditions than the laboratory studies. As noted, the AWPA revised their standards to limit the commercial practices to those that were found to be nondamaging to the wood. Improper attention to any of these factors could have the potential for adversely increasing observed effects in service.

There are also questions regarding the actual temperatures incurred during service. Heyer (1963) reported temperature data on houses using older construction techniques. In his testing of seven different structures in Oregon, Arizona, Texas, Georgia, and Wisconsin, the Georgia site proved to be the most severe. For the hottest summer recorded, he found the following thermal loadings at the shingle/sheathing interface: 66 – 70.5°C, 43 h; 71 – 76°C, 20 h; and 77 – 82°C, 1 h. On the attic side of the sheathing, no temperature readings exceeded 66°C except for 1 h at 71 – 76°C.

Comprehensive temperature data with new construction technologies were developed under a cooperative study between the University of Illinois and the USDA FPL. The first report from this work indicated that the sheathing gets much hotter than that reported by Heyer (Rose 1992). Interpolating from the Rose figures, the following approximate thermal loadings for the roof membrane/sheathing interface in unvented, flat-ceiling attics located in central Illinois on an annual basis were obtained: 66 – 70.5°C, 85 h;

71 – 76°C, 62 h; and 77 – 82°C, 7 h. The exposure for cathedral ceiling assemblies on an annual basis was even more severe with the following approximate maximum loadings reported: 66 – 70.5°C, 93 h; 71 – 76°C, 70 h; 77 – 82°C, 37 h; and >82°C, 9 h. Constructions in which either batt or rigid foam insulation was placed in physical contact with the underside of the sheathing yielded the most severe temperatures.

Significantly, Rose (1992) also showed that sheathing in unvented cavities was exposed to significantly higher MC than previously expected. MC in excess of 30% was reported. These observations tend to lend credence to the concept that construction techniques leading to high-MC/high-temperature environments may be the controlling factor or at least a significant factor in the in-service degradation phenomenon sometimes observed in the field.

More recent work has documented the attic temperatures in matched roof systems located in southern Wisconsin and east-central Mississippi (Winandy et al 2000). This work compared white and black shingle roofs in dry and wet conditions and also recorded the attic framing temperatures over 4- or 8-yr periods. Roofs with black shingles tended to be about 5 – 10°C warmer during the midafternoon of a sunny day than comparable white-shingled roofs. The highest temperatures were recorded in Mississippi and on an annual basis, the top of the roof sheathing averaged 194 h at 60 – 65°C, 64 h at 66 – 70°C, and 2 h at 71 – 76°C over the 4-yr measurement period. The sheathing bottom highest temperature on an annual basis averaged 13 h at 60°C over the 4-yr exposure. This work substantiated the selection of laboratory test exposures of 66 – 77°C that were selected for the various earlier ASTM protocols.

The objective of this study was to determine the relationship between matched laboratory and field results based on strength–temperature–RH (MC)–FR chemical interactions. The impact of the variables was evaluated by measuring bending strength properties for matched laboratory- and field-exposed samples. A preliminary discussion of MOR was discussed previously as Part 1 (Barnes et al 2008), but this article presents all of the strength property data. Current model studies have generally been limited to isothermal rate studies with selected model FR chemicals. We believe, however, that other factors also play a major role in the degradation of FR-treated wood. These factors, which have not been studied in any detail, include RH/MC cycles and thermally induced evolution of ammonia from ammonium phosphates, which results in elevated levels of phosphoric acid. If we are to understand and accurately model the degradation of treated and untreated wood, it will be necessary to obtain sufficient and comprehensive data from matched laboratory and field studies to establish creditable acceptance criteria for evaluating FRT wood. There exists no known direct comparison of matched samples with one exposed to high-temperature laboratory conditions and the other exposed for an extended period of time as traditionally used in North American light-framed construction.

This part of the overall study concentrates on static bending results from the Mississippi panels compared with the laboratory panels. Subsequent publications will center on the other aspects of the overall study, including development of predictive models of the laboratory-to-field relationship.

MATERIALS AND METHODS

Exposure Structures

A series of exposure structures, 3.7 m wide × 4.9 m long, identical to those in test at the USDA FPL Valley View test site outside of Madison, WI (Winandy and Beaumont 1995), were constructed at the Mississippi Forest Products Laboratory, Mississippi State University. The exposure structures were constructed as platforms in which plywood specimens can be exposed to diurnal/seasonal cyclic field conditions. Each roof was south-facing with a 3:12 pitch and constructed such that samples can be inserted into frames providing direct contact with the shingle/roof felt roofing membrane

(see Figs 1 and 2). Black shingles were used to ensure maximum heat absorption. This direct thermal contact provided conditions similar to those experienced by full-sized sheets of treated roof sheathing. Temperature in the structures were monitored by thermocouples positioned in the following locations: 1) outside; 2) between felt and the top surface of the roof sheathing; 3) inside the structures; 4) inside the simulated living spaces; 5) at the midpoint of an interior rafter; and 6) at the bottom surface of the roof sheathing. Further details are available in a previous paper addressing the effect of shingle color/thermal absorptivity (Winandy et al 2000).

Figure 1. Experimental field exposure units.

Figure 2. Interior view of exposure units showing data acquisition system (upper) and exposure portals (lower) for plywood samples.

Two structures were designated as the DRY-DRY buildings for plywood that was kiln-dried after treatment (KDAT) and installed and maintained in a dry structure. These two structures also represent the assumed typical exposure for roof sheathing in which the panels are installed dry and kept dry. These two structures had no ingress or egress of ambient air so that the DRY building would match the WET buildings discussed subsequently. The two DRY structures provided twice as many samples as the other conditions allowed so that this critical baseline (ie the normal assumption of design condition) exposure could be carefully documented.

Two additional structures provided data not currently considered in design. In both of these structures, humidified air was supplied periodically to maintain a high RH (>85%) environment. (Note: this high humidity was used to accelerate any possible degradation from humidity and is not representative of in-service humidities.) RH within each structure was monitored on a periodic basis to develop a temperature/RH profile for each structure. It was not possible to ventilate these structures and maintain the humidity. One humidified chamber was used to test samples of plywood sheathing, which were KDAT and rewetted by immersion before exposure (DRY-WET structure). The other was used to expose treated samples that were not dried before exposure (ie installed wet from treating) and this structure was referred to as WET-WET. (The untreated panels for the WET-WET condition were treated with only water and installed wet.) The groups that were not dried after treatment and were exposed wet were meant to ascertain problems associated with rewetting in service. This latter exposure was intended to provide a worst case scenario.

Plywood

Twenty sheets of 16-mm-thick, 4-ply southern pine plywood made with defect-free N-grade veneer were used to reduce variability in mechanical properties resulting from random placement of defects in interior veneers. From each sheet, 48 samples, 102 × 559 mm parallel to face grain were cut. The specimen size, although not exactly that specified in ASTM D-3043 (ASTM 1991), is similar and was selected to fit between attic roof rafters set 610 mm on center (Winandy and Beaumont 1995; Winandy et al 2000). One sample from each sheet was randomly assigned to 48 experimental groups in a blocked experimental design. This allowed within-panel variation to be separated from between-panel variation, thus greatly increasing the sensitivity of the statistical analysis. Each sample was evaluated for stress-wave transit time and waveform damping before treatment. Some groups were randomly selected as untreated controls. Others were assigned to the treatments described subsequently. Table 1 shows the experimental design for this study. Forty-four of the 48 experimental groups were required in the testing/exposure protocol and four were used for other work. Use of this procedure provided sample groups that were closely matched in specific gravity and no correction was necessary for the slight differences.

Treatment

Three model FR formulations were studied. A formulation of unbuffered 100% monoammonium phosphate (MAP), representative of an unbuffered system, served as the basis for comparison with earlier studies (Winandy et al 1991a). Mixtures of 75% MAP/25% phosphoric acid (PA) and 50% MAP/30% PA/20% disodiumoctaborate tetrahydrate, representative of acidic and buffered systems, respectively, were also used. All samples were pressure-treated using a full-cell treatment cycle to a nominal 48 kg/m^3 (Table 2).

This nominal retention approximates the required retention for southern pine plywood with commercially available formulations. Samples designated as KDAT were dried to approximately 15% MC using 71°C dry-bulb and 54°C wet-bulb temperatures. These materials were then equilibrated to constant weight at 23°C, 65% RH before installation into the test structures or steady-state exposure in laboratory tests as described subsequently.

Sample Exposures

Laboratory exposure. Selected groups were placed in a controlled environment at 66°C, 75% RH for 2 or 6 mo (Table 1) as prescribed in ASTM 5516 (ASTM 2008a). After the appropriate exposure period, samples were reconditioned as before the exposure and tested.

Field exposure. Selected groups were exposed to field conditions in the exposure structures for 12 or 43 mo (Table 1). Because of the limited number of sample locations in the structures, the samples were exposed as two discrete sets. One set was exposed for 1 yr (368 da) and the second set was exposed for 3.6 yr (1305 da). An important point is that the 3.6 yr consisted of

Table 1. *Experimental design showing days (months) and years of exposure in each environment.*[a]

Treatment	Control[b]	Steady-state laboratory exposure (66°C, 75% RH)	KDAT unvented DRY- DRY (DD)	Field exposures KDAT >85% RH DRY-WET (DW)	No KDAT >85% RH WET-WET (WW)
	[days (months) years]				
100% MAP	0 (0) 0	60 (1.97) 0.16		368 (12.10) 1.01	
75% MAP + 25% PA (MPA)	0 (0) 0				
50% MAP + 30% PA + 20% DOT (MPT)	0 (0) 0	180 (5.92) 0.49		1305 (42.90) 3.58	
Untreated	0 (0) 0				

[a] One experimental group of 20, except for 40 untreated, unexposed samples and 40 in the DD group, was tested for each time period indicated.
[b] Represents the unexposed control.
DOT, disodiumoctaborate tetrahydrate.

Table 2. *Average treatment retentions.*

Component	MAP	PA	DOT	Total
Treatment		kg/m^3		
MAP	51.4	—	—	51.4
MPA	44.1	12.9	—	57.0
MPT	27.0	15.9	11.5	54.3

DOT, disodiumoctaborate tetrahydrate.

four springs, summers, and falls with only three winters so that the estimate of the temperature exposure is conservative. Temperature profile information was acquired during these same periods as shown in Fig 3. After the appropriate exposure, samples were reconditioned in the 12% EMC chamber before testing.

Mechanical Testing

After conclusion of the specified exposure period, each sample was conditioned as described previously and then tested to failure in bending using center-point loading (ASTM 1991). Load, center-span deflection, and rotation at the load-head-to-specimen contact point were recorded. Modulus of elasticity (MOE), MOR, and work-to-maximum load (WML) were calculated using the actual thicknesses and MC at the time of testing and specific gravity was determined. This close matching of specimens and strength testing parameters permitted all subsequent data analysis to be based on a comparison of the ratios of the values for the exposed treated and untreated groups to the unexposed, untreated control group. Analysis of variance using specific gravity as a covariate was performed (SAS 2008). Tukey's test was used for means separation.

RESULTS AND DISCUSSION

The grouped mean values for MOR, MOE, and WML of matched plywood specimens variously exposed to steady-state laboratory and diurnal/seasonally cyclic field exposures are shown in Tables 3 and 4, respectively. The MC and specific gravity data for the laboratory and field exposures are given in Tables 3 and 4, respectively. The mechanical property data were not adjusted for MC because the three different treatments each tend to increase equilibrium

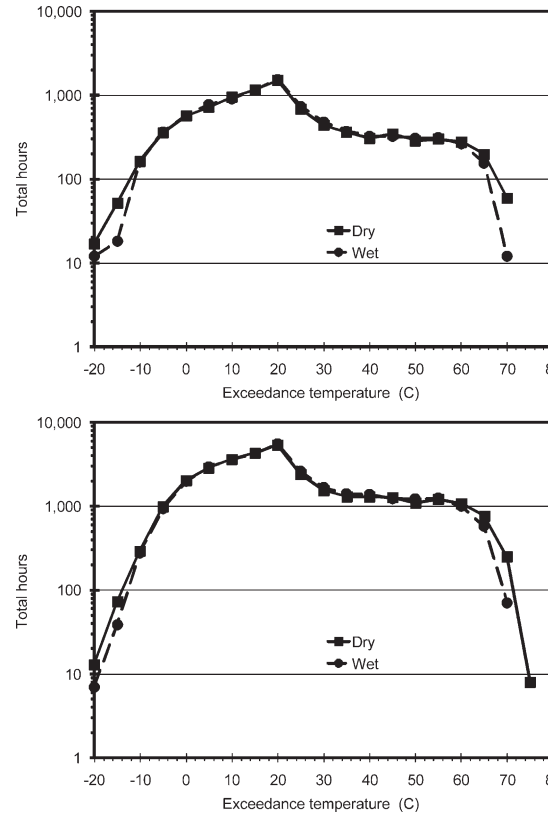

Figure 3. Temperature loads during the 1-yr (upper) and the 3.6-yr (lower) exposure periods.

MC by about 1 – 2%, but this MC increase is a characteristic of the treatment and any MC-related adjustment would tend to mask either the treatment or in-service effect, or both.

For ease of comparison, it was decided to express the data as the ratio of the exposed, treated, and untreated groups to the unexposed, untreated group. Those comparative ratios are given in Table 5. All subsequent discussion of the data for the remainder of this publication relates to these ratios.

Laboratory Exposure

MOR. Comparative ratios of the MOR data for the laboratory steady-state exposure at 66°C and 75% RH are given in Table 5. Linear regressions of these ratios are shown in Fig 4. Such linear regressions, as used in this analysis,

Table 3. *Mean values for static bending testing from the laboratory study at 66°C, 75% RH.*

	MOE (MPa)			
Years	MAP	MPA	MPT	Untreated
0	9,163	9,074	8,577	9,108
0.16	8,301	8,281	8,308	9,039
0.49	11,700	7,433	7,908	8,584
	MOR (MPa)			
Years	MAP	MPA	MPT	Untreated
0	56.7	55.5	54.7	70.3
0.16	39.3	36.9	39.6	58.2
0.49	27.0	24.0	24.8	55.0
	WML (kJ/m^3)			
Years	MAP	MPA	MPT	Untreated
0	38.7	32.6	33.6	46.2
0.16	14.7	13.9	16.0	33.3
0.49	7.0	5.7	5.5	32.1
	Specific gravity			
Years	MAP	MPA	MPT	Untreated
0	0.632	0.629	0.62	0.627
0.16	0.631	0.614	0.614	0.614
0.49	0.584	0.582	0.587	0.598
	MC (%)			
Years	MAP	MPA	MPT	Untreated
0	12.6	12.6	13.1	10
0.16	12.7	13.0	13.1	12.1
0.49	13.5	13.8	13.2	11.9

Table 4. *Mean values for static bending testing of treated plywood exposed in field tests.*

		MOE (MPa)			
Exposure	Years	MAP	MPA	MPT	Untreated
DRY-DRY	1.01	9,253	8,936	8,756	9,632
	3.58	9,453	9,460	9,156	9,508
DRY-WET	1.01	9,060	9,177	9,156	9,618
	3.58	9,563	8,777	8,867	10,259
WET-WET	1.01	8,701	8,522	8,653	9,211
	3.58	9,142	9,122	9,280	9,501
Control	0	9,163	9,074	8,577	9,108
		MOR (MPa)			
Exposure	Years	MAP	MPA	MPT	Untreated
DRY-DRY	1.01	55.3	50.5	49.8	66.2
	3.58	50.3	44.8	42.7	65.5
DRY-WET	1.01	55.3	51.4	49.7	61.8
	3.58	48.6	36.9	41.7	64.8
WET-WET	1.01	51.7	46.7	47.4	56.8
	3.58	36.5	36.5	40.7	59.4
Control	0	56.7	55.5	54.7	70.3
		WML (kJ/m^3)			
Exposure	Years	MAP	MPA	MPT	Untreated
DRY-DRY	1.01	30.5	23.4	23.4	40.6
	3.58	19.4	14.3	13.9	37.9
DRY-WET	1.01	34.4	26.7	23.2	44.8
	3.58	17.3	11.4	13.9	37.2
WET-WET	1.01	28.3	22.8	22.8	32.3
	3.58	22.3	9.9	13.2	31.3
Control	0	38.7	32.6	33.6	46.2
		MC (%)			
Exposure	Years	MAP	MPA	MPT	Untreated
DRY-DRY	1.01	10.2	10	10.6	9.2
	3.58	9.4	9.4	9.9	9.1
DRY-WET	1.01	12.2	11.9	12.7	11.7
	3.58	11.1	10.9	11.6	11.2
WET-WET	1.01	12.8	12.7	13.4	12.6
	3.58	11.2	10.9	11.6	11.1
Control	0	12.6	12.6	13.1	10
		Specific gravity			
Exposure	Years	MAP	MPA	MPT	Untreated
DRY-DRY	1.01	0.641	0.632	0.628	0.627
	3.58	0.675	0.687	0.673	0.66
DRY-WET	1.01	0.625	0.623	0.624	0.606
	3.58	0.693	0.692	0.68	0.682
WET-WET	1.01	0.62	0.616	0.616	0.602
	3.58	0.658	0.625	0.64	0.611
Control	0	0.632	0.629	0.62	0.627

are sometimes considered to be better fit by a logarithmic function, but with only three time elements, such analysis might be considered overfitting the data. It should be noted that such a linear fit often overexaggerates the rate losses and more sophisticated models may be appropriate if additional time elements were available (Winandy and Lebow 1996; Lebow and Winandy 1999, 2003; Winandy et al 2002).

First, it should be noted that the initial MOR losses for all of the FR formulations were about 20%. This change agrees well with the long-standing recommendation to reduce the design values by 16.7% if plywood is treated with fire retardants (APA 1965). Also note that the laboratory-exposed samples have experienced considerably more rapid strength losses compared with the field-exposed samples. This was expected because LeVan et al (1995) showed that continuous exposure in a laboratory test showed much higher strength loss than cyclic exposures. However, when Levan et al (1995) compared the strength data on the basis of the amount of time at the same temperature, the strength losses for the cyclic and continuous

Table 5. *Property ratios relative to unexposed, untreated controls.*

Exposure	Years	Ratio of treated/untreated MOR			
		MAP	MPA	MPT	Untreated
Control	0	0.81	0.79	0.78	1.000
Laboratory 66°C, 75% RH	0.16	0.56	0.53	0.56	0.83
	0.49	0.38	0.34	0.35	0.78
$LSD_{\alpha=0.05}$	0.148	Means separated by > $LSD_{\alpha=0.05}$ are significantly different at $\alpha = 0.05$			
Exposure	Years	Ratio of treated/untreated MOR			
		MAP	MPA	MPT	Untreated
DRY-DRY	1.01	0.79	0.72	0.71	0.94
	3.58	0.71	0.64	0.61	0.93
DRY-WET	1.01	0.79	0.73	0.71	0.88
	3.58	0.69	0.53	0.59	0.92
WET-WET	1.01	0.67	0.67	0.67	0.81
	3.58	0.71	0.52	0.58	0.84
$LSD_{\alpha=0.05}$	0.175	Means separated by > $LSD_{\alpha=0.05}$ are significantly different at $\alpha = 0.05$			
Exposure	Years	Ratio of treated/untreated WML			
		MAP	MPA	MPT	Untreated
Control	0	0.84	0.71	0.73	1.00
Laboratory 66°C, 75% RH	0.16	0.32	0.30	0.35	0.72
	0.49	0.15	0.12	0.12	0.69
$LSD_{\alpha=0.05}$	0.273	Means separated by > $LSD_{\alpha=0.05}$ are significantly different at $\alpha = 0.05$			
Exposure	Years	Ratio of treated/untreated WML			
		MAP	MPA	MPT	Untreated
DRY-DRY	1.01	0.66	0.51	0.51	0.88
	3.58	0.42	0.31	0.30	0.82
DRY-WET	1.01	0.75	0.58	0.50	0.97
	3.58	0.37	0.25	0.30	0.81
WET-WET	1.01	0.61	0.49	0.50	0.70
	3.58	0.48	0.21	0.29	0.68
$LSD_{\alpha=0.05}$	0.339	Means separated by > $LSD_{\alpha=0.05}$ are significantly different at $\alpha = 0.05$			

LSD, least significant difference.

exposures are the same for the same amount of time at a given temperature.

In this study, the untreated samples sustained 17 and 22% loss in MOR after 2 and 6 mo, respectively, of steady-state laboratory exposure at 66°C and 67% RH. The matched sets of three tested treatments were each reduced by a similar level showing an additional loss of about 28 – 33% MOR at 2 mo and 52 – 57% at 6 mo of steady-state exposure at 66°C and 67% RH (Fig 4). There was little to no difference among the various treatments in this laboratory exposure because we either increased the acid content like with the MPA treatment or added a pH buffer like in the MPT treatment when compared with the MAP treatment alone. This finding suggests that the laboratory exposure essentially overwhelms any effects from the various treatments. As seen later, the losses sustained in the laboratory are considerably larger than those obtained under the field exposure conditions. Presumably this is because there is significantly more heat exposure during an hour of constant temperature laboratory exposure than during a typical hour of field exposure with its varying temperature.

MOE. Compared with the original untreated, unexposed values, there was a 6% loss in MOE for the untreated samples exposed for 6 mo in the laboratory. The MAP-treated samples showed a gain in MOE. The MPA-treated samples lost 18% and the buffered MPT had a 13% loss.

When the results are compared against the untreated but exposed samples, the MOE losses after 6 mo are 13 and 8% for the MPA and

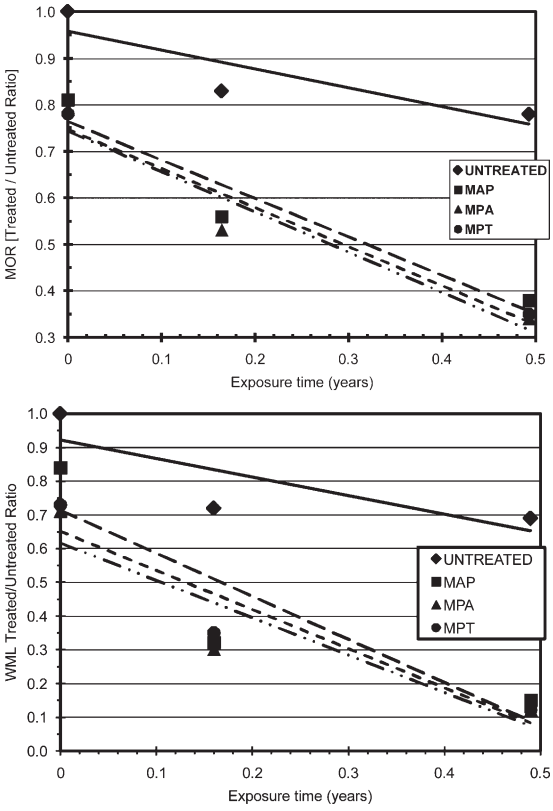

Figure 4. Comparison of treated/untreated MOR (upper) and WML (lower) ratios in the laboratory study.

MPT systems, respectively, with the MAP system showing an increase. When these MOE values were compared statistically, no significant loss in MOE compared with untreated was noted.

WML. The untreated samples had a 31% loss in WML from the laboratory exposure; however, this exposure basically overwhelmed the treated samples. These were essentially 85% or more when compared with the untreated, unexposed value. The effect of the FR model compounds can be easily seen if the ratios of WML are compared before exposure. At zero time when the effect is solely from the treatment, the MAP samples showed a 16% loss. The MPA had almost double that with a 29% loss and the buffering MPT treatment reduced the loss somewhat. This again shows the benefits of buffer incorporation into the FR formulations.

When compared with the untreated, exposed samples, the treated samples had WML losses of about 80%. This loss is made up of about a 20% loss from the treatment and 60% loss from exposure.

Field Exposure

MOR. Untreated plywood showed a 7% total loss when exposed in the DRY-DRY condition and 8% total loss when exposed in the DRY-WET condition for 3.6 yr (Table 5; Figs 5 – 7). The total losses in the WET-WET condition at 16% after 3.6 yr were about twice the previously described losses. This demonstrates that continual moisture provides the worst case exposure condition for plywood.

After 3.6 yr, plywood treated with MAP alone showed additional losses of 10, 12, and 10% for the DRY-DRY, DRY-WET, and WET-WET conditions, respectively, after the initial treatment losses. This shows that MAP alone is relatively insensitive to moisture because essentially the same degree of loss is shown for all conditions.

Addition of PA to MAP showed a 21% initial loss, which is similar to the initial loss for MAP alone. However, 3.6-yr field exposure greatly increased the total losses. Under the DRY-DRY conditions, the loss increased by 15% at 3.6 yr to a total of 36%. This formulation had further decreases in strength from moisture with the DRY-WET samples losing 47% total and the WET-WET conditions losing 48% total. The two wet conditions increased losses by 11 – 12% from the DRY-DRY. This indicates that moisture exacerbates the attack of the acid-containing formulation.

The buffered FR model compound MPT had an initial loss of 22%, which is essentially the same as the other treatments. Interestingly, the buffer showed the same loss regardless of the moisture conditions with the 3-yr losses increasing 17, 19, and 20% for the DRY-DRY, DRY-WET,

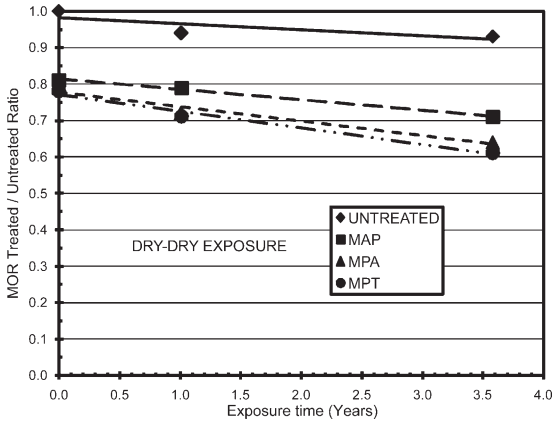

Figure 5. Ratio of treated/untreated MOR for samples exposed in the DRY-DRY condition.

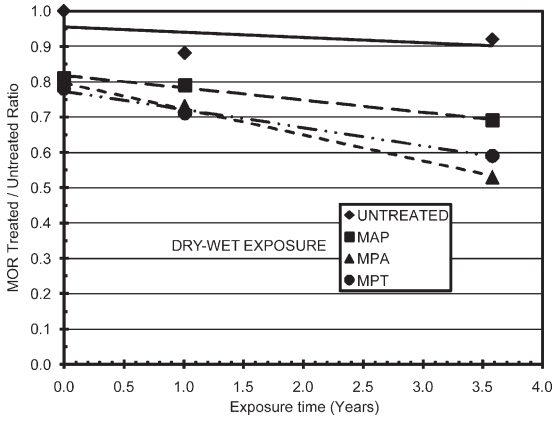

Figure 6. Treated/untreated MOR ratio for samples exposed under DRY-WET conditions.

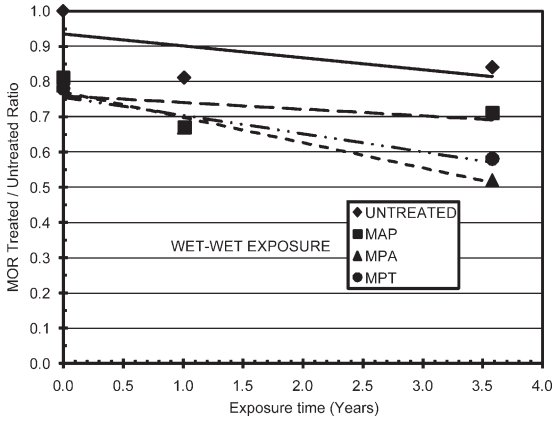

Figure 7. Ratio of treated/untreated MOR for wet samples exposed under wet conditions.

and WET-WET conditions, respectively. When compared with the losses for the MPA, these are 3% worse for the DRY-DRY but 6% better for both moisture conditions. This shows MPT to be intermediate in effect on long-term field exposure when compared with MAP or MPA. It would also appear that the buffer required some moisture to be effective.

An analysis of the rate of loss in MOR (slopes of the curves in Figs 5 – 7) for the various exposure conditions was performed. For the DRY-DRY exposure, the MPA treatment was significantly different at the $p = 0.1$ level. The rates for the other treatments were not significantly different. For the DRY-WET exposure, the MPA treatment was significantly higher than the untreated, whereas the MAP and MPT treatments were equivalent to the untreated samples and to each other. For the WET-WET exposure, rates were equivalent for MA and MPT when compared with untreated, whereas MPA was significantly higher than the untreated.

That there was substantially less effect on significantly longer-exposed specimens clearly indicates that high-temperature, steady-state laboratory exposures are far more deleterious on plywood properties than are diurnal/seasonally cyclic real-world field exposures. This may indicate the existence of a "thermal inertia" barrier, which must be overcome before any effects are seen.

MOE. When compared with the untreated, unexposed sample values, the MOE values were not significantly affected after 43 mo of exposure. With the exception of one value, all were within 6% of the untreated values. The one unusual case was the DRY-WET exposure for the untreated in which the MOE increased by 13% compared with the original unexposed MOE. Because this unusual value was for the untreated material, there was obviously no effect resulting from the FR model compounds on the MOE.

WML. The WML values were statistically significant and, in some cases, relatively large

(Table 5; Figs 8 – 10). The untreated material showed a 20% loss for the DRY-DRY condition after 43 mo, whereas the loss for the WET-WET condition was 32%. In relative terms, the WET-WET condition increased the loss by over 50%.

The MAP-treated samples had losses of 50 – 60% total depending on the exposure conditions. In this case, the WET-WET condition had the least effect with a 52% loss. Also, with the MAP-treated samples, there was an initial loss to the first evaluation at 12 mo and then there was a fairly constant 40% loss after the initial loss.

As expected, the MPA-treated samples had the largest losses and these were in the 70 – 80% range. Clearly, the lack of a buffer exacerbates the acid effect. Addition of the buffer for the MPT-treated samples modified the losses to a constant 70% regardless of the exposure conditions. Another interesting comparison is that for the 12-mo exposures, the MAP samples have routinely about 10 – 15% less loss than the MPA samples. Again this shows that unbuffered acid can quickly exert its effect.

There are also WML losses when the treated samples are compared with untreated, exposed samples. In this case, the losses for the MAP-treated samples are 30 – 50% depending on the building exposure. For the MPA-treated samples, the losses are 60 – 70% and the MPT samples are 60 – 65%. The same trends in which the buffer improves the losses also occur in this comparison. Graphs for these loss rates are shown in Figs 8 – 10 for the three exposure conditions.

Formulations

It should be re-emphasized that the formulations selected for this work were chosen to simulate possible scenarios and are not representative of actual commercial formulations. To the authors' knowledge, there are no commercial formulations that are purely MAP, but rather formulations based on MAP always have incorporated

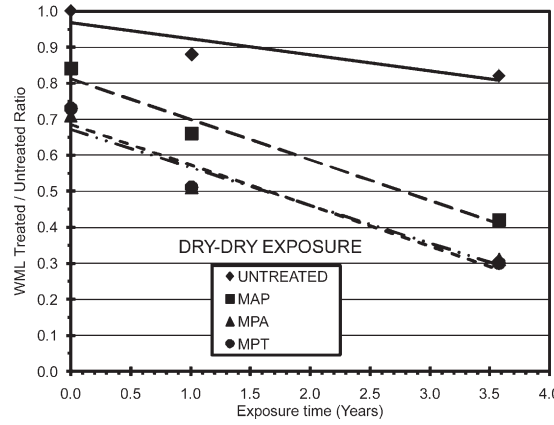

Figure 8. Ratio of treated/untreated WML for samples exposed in the DRY-DRY condition.

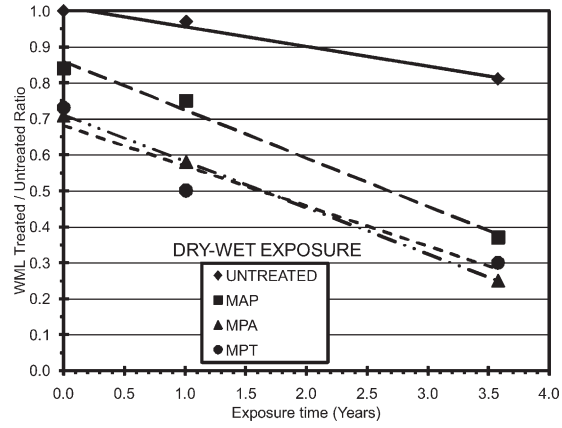

Figure 9. Treated/untreated WML ratio for samples exposed under DRY-WET conditions.

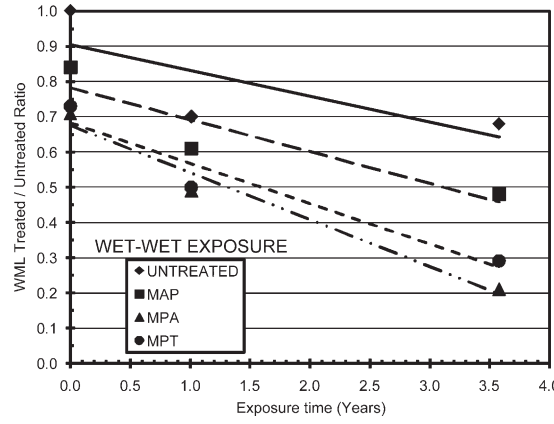

Figure 10. Ratio of treated/untreated WML for wet samples exposed under wet conditions.

borate buffers. Obviously, there are no commercial formulations that purposely incorporate PA and its inclusion in this work was to simulate the possible in situ formation of PA during extended exposure periods. As noted, the formulations in this work were chosen to help elucidate possible mechanisms of strength loss during exposure and accelerate such losses into a reasonable timeframe. However, when free acid is added to the formulation and the moisture increased, then additional strength loss over and above the initial loss occurs. Buffering the formulation with borate helps resist some of the acid degradation.

SUMMARY AND CONCLUSIONS

A series of laboratory and field tests were designed to investigate the impact of exposure conditions on the strength of southern pine plywood treated with model fire-retardant compounds. This report has shown that steady-state laboratory conditions are much more severe than those found in the field. Although strength loss rates were essentially equal for both untreated and treated specimens exposed under dry, ambient conditions in the field, increasing the moisture loading increased the strength loss for systems containing free phosphoric acid. This suggests that the role of humidity for in-service performance may be larger than heretofore believed. There may also be additional factors involved with the real-life performance because there were reports of relatively sudden failures of FRT plywood. MAP alone has little impact on the degradation rate compared with untreated wood. Buffering the system with borates was shown to help resist some of the effects of acid degradation.

Future papers on modeling will correlate time of exposure in a steady-state high-temperature laboratory exposure chamber to matched data exposed under diurnal/seasonally cyclic field conditions. This analysis is currently underway and will enable direct correlation of laboratory and field exposure data. Effectively, these models will be helpful in ASTM standard practices such as D6305 for plywood and D6841 for lumber that allow engineers to calculate adjustment factors for FR-treated wood materials exposed to intermittent high-temperature conditions in-service.

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