LABORATORY AND FIELD EXPOSURES OF FIRE RETARDANT-TREATED PLYWOOD: PART 3—MODELING EXPOSURE RELATIONSHIPS

J. E. Winandy†*

Adjunct Professor
Department of Bioproducts and Biosystems Engineering
University of Minnesota
St. Paul, MN
E-mail: jwinandy@umn.edu

H. M. Barnes†

Thompson Distinguished Professor of Wood Science & Technology
E-mail: mbarnes@cfr.msstate.edu

P. D. Jones†

Associate Professor/Extension Specialist
Department of Sustainable Bioproducts
Mississippi State University
Mississippi State, MS 39762-5724
E-mail: pdjones@cfr.msstate.edu

C. R. McIntyre†

Principal
McIntyre Associates, Inc.
Dayton, MT 59914-02202
E-mail: craig@mcintyre-inc.com

(Received March 2014)

Abstract. Our understanding of how to relate 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 studies have generally been limited to isothermal rate studies with selected model FR chemicals. Currently, no known direct comparison exists of matched sets of samples with one set 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 (moisture content)–FR chemical interactions. Two previous studies evaluated the effects of various exposures on bending strength properties and directly compared matched laboratory- and field-exposure samples. This study presents an empirical model to relate the differential effects of laboratory and field exposures on changes in mechanical properties for matched samples.

Keywords: Fire retardants, strength, plywood, laboratory-to-field exposure correlation.

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 resulting in millions of dollars of litigation and roof replacement. Our understanding of field-induced degradation is currently limited because we are unable to correlate laboratory steady-state experiments with actual in-service field degradation. Debate

* Corresponding author
† SWST member

still exists as to the relative influence of various material, construction, 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.

During the last 25 yr, a relatively large database of steady-state laboratory exposure to elevated temperatures has been developed by Barnes et al (2010), Winandy (1997, 2001, 2013), and Winandy et al (1991). This work led to two ASTM standard test methods, one for FRT plywood (ASTM 2008a) and another for FRT lumber (ASTM 2008b). Subsequent ASTM standard practices, such as ASTM (2008c) for plywood and ASTM (2008d) for lumber, were also developed to allow engineers to calculate adjustment factors for FRT wood materials exposed in service to intermittent high-temperature conditions based on the results derived from ASTM D5516 (2008a) and ASTM D5664 (2008b) test results. Still, no definitive relationship exists between laboratory and field exposures for the effects on wood strength loss of FRT.

BACKGROUND

In virtually all the FRT effect studies during the last 25 yr, the magnitude of the differences was generally attributable to the FRT used and the exposure temperature conditions studied. 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, it was postulated that differences among in-service performances of FR systems were related to the initial time required for the chemical to dissociate at specific temperatures into its acidic chemical form (Winandy 2001). Based on chemical analyses, LeVan and Winandy (1990) postulated that breakdown of the hemicellulose fraction in wood was primarily responsible for the strength losses encountered. That hypothesis was confirmed by subsequent work (Winandy and Lebow 2001).

Current model studies are generally 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 FRT wood. These factors, which have not been studied in any detail, include RH–moisture content 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. No known direct comparison exists between matched samples exposed to high-temperature laboratory conditions and field exposed samples over an extended period of time as traditionally used in North American light-framed construction.

The relationship between steady-state laboratory exposure and constantly changing field exposure is not well defined. In an attempt to elucidate moisture effects, LeVan et al (1996) conducted a cyclic exposure study in which temperature varied daily between 27 and 66°C at either 6 or 12% MC in untreated wood. Exposure times varied from 215 da for the 6% samples to 400 da for the 12% samples. LeVan et al (1996) 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 LeVan et al (1996) to conclude that no difference existed from high-temperature exposure between 6 and 12% MC.

Barnes et al (2008, 2010) compared a series of matched plywood samples in high-temperature, steady-state laboratory exposure and cyclic, diurnal field exposure for up to 3.5 yr. The tests investigated the impact of exposure conditions on the strength of southern pine plywood treated with model FR compounds. They found that steady-state laboratory conditions were much more severe than those in the field. They also studied the effects of in-service moisture exposure and found that 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. That result suggested that the role of humidity for in-service performance may be greater than previously thought.

A previous study documented attic temperatures in matched roof systems located in southern Wisconsin and east–central Mississippi (Winandy et al 2000). This study compared white and black shingle roofs in dry and wet conditions and also recorded the attic framing temperatures for 4 and 8 yr. 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 its roof sheathing averaged 194 h at 60-65°C, 64 h at 66-70°C, and 2 h at 71-76°C during the 4-yr measurement period. On an annual basis, the bottom of the sheathing averaged 13 h at 60°C during the 4-yr exposure, which was its highest temperature. This work substantiated the selection of laboratory test exposures of 66-77°C, which were selected for the various ASTM protocols previously mentioned.

During the Winandy et al (2000) study, matched plywood samples were simultaneously exposed to either a high-temperature, steady-state laboratory exposure or a cyclic, diurnal field exposure for up to 3.5 yr in Mississippi and 8 yr in Wisconsin. The physical and mechanical property data from that work were presented in our first two studies in this series (Barnes et al 2008, 2010).

The objective of this third study in the series was to model the relationship between laboratory and field exposures of matched plywood strength property data presented in our two previous studies in this series.

MATERIALS AND METHODS

Exposures

Field exposures were conducted by inserting small 102- × 559-mm, 16-mm-thick, four-ply southern pine plywood specimens in open slots in the roof sheathing of the field-exposure structures. Matched groups of these specimens were field-exposed for 1 or 3.5 yr. The construction and design of the field-exposure structures, the plywood materials, and a description of the high-temperature, steady-state laboratory exposure chamber were previously described in detail in our first two studies (Barnes et al 2008, 2010). The high-temperature, steady-state laboratory exposures used matched untreated pine plywood specimens cut from the same original panels as the treated plywood and were conducted at 65°C and 75% RH for 60 or 160 da. More complete exposure details and physical and mechanical testing protocols were also detailed in those two studies. The grouped mean values for bending strength (ie modulus of rupture [MOR], modulus of elasticity [MOE], and work to maximum load [WML]) of matched plywood specimens after exposure to either steady-state laboratory or diurnal–seasonally cyclic field exposures were previously reported by Barnes et al (2010). MOR results are shown in Table 1.

Formulations

Three generic FR formulations were evaluated. The first was monoammonium phosphate (MAP) as a 100% concentrate. The other two concentrates were a 75–25% mixture of MAP and phosphoric acid (PA), respectfully (hereafter referred to as MPA), and a 50-30–20% mixture of MAP, PA, and disodium octaborate, respectively (hereafter referred to as MPD). Each concentrated formulation was individually diluted to make up a 14% treating solution used to treat the plywood in a pressure vessel to a target loading of 56 kg/m^3. All three FR systems used this same target loading.

The formulations in this program were chosen to help elucidate possible mechanisms of strength loss during exposure and accelerate such losses into a reasonable timeframe. Experience has shown that when free acid is added to a FR formulation and the moisture is increased, additional strength loss occurs. Buffering the

Table 1. Nonparametric rank-order analysis for modulus of rupture (MOR) of matched untreated and treated[a] plywood specimens exposed to in laboratory or in a field environment in simulated roof structures for 1 or 3 yr in Mississippi.

MOR (MPa)	Exposure	Control	Laboratory	Laboratory	Field	Field
		0 da	60 da	160 da	368 da	1305 da
Untreated						
No.		20	16	20	40	39
Mean		70.3	58.3	55.0	66.2	65.5
SD[b]		13.9	12.2	9.3	13.3	13.4
90%		87.7	73.2	65.4	83.3	82.1
75%		82.0	67.8	62.3	75.9	76.7
50%		73.8	59.2	56.1	65.6	66.7
25%		57.8	51.9	48.5	58.1	56.0
10%		52.0	37.6	41.4	51.3	48.6
MAP-treated						
No.		20	15	20	40	40
Mean		56.7	39.3	27.0	55.4	50.3
SD		8.0	7.8	8.8	10.3	10.5
90%		64.6	48.1	36.0	68.5	64.1
75%		62.6	47.3	32.6	63.5	58.8
50%		58.8	41.0	28.4	56.2	48.7
25%		52.9	34.0	21.3	48.2	41.5
10%		43.6	30.0	12.7	43.6	38.4
MPA-treated						
No.		20	20	20	40	40
Mean		55.5	36.9	24.0	50.5	44.8
SD		9.4	9.3	6.6	11.9	14.4
90%		64.8	49.8	32.3	65.0	65.0
75%		64.0	46.5	29.4	57.9	52.4
50%		57.8	34.7	24.1	48.6	42.4
25%		47.7	28.6	18.6	45.0	34.4
10%		41.5	25.7	14.5	34.2	31.0
MPD-treated						
No.		19	20	18	40	40
Mean		53.8	39.0	24.9	49.9	42.7
SD		11.4	9.1	8.0	11.3	10.0
90%		68.8	52.7	36.0	66.5	58.1
75%		64.7	44.9	30.3	56.2	49.4
50%		52.4	40.1	26.2	50.9	43.3
25%		45.6	31.5	18.4	43.4	35.9
10%		42.7	25.5	14.0	33.6	29.1

[a] MAP, monoammonium phosphate; MPA, 75% MAP and 25% phosphoric acid; MPD, 50% MAP, 30% phosphoric acid, and 20% disodium octaborate.
[b] SD, standard deviation.

formulation with borate helps it resist some acid degradation.

The three formulations selected for this work were chosen to simulate possible FR formulation scenarios and are not directly representative of any actual commercial formulations. To our knowledge, there are no commercial formulations that are purely MAP, but rather formulations based on MAP always have borate buffers incorporated. Obviously, there are no commercial formulations that purposely incorporate PA. Its inclusion in this work was to simulate the possible in situ formation of PA during extended exposure.

Analysis and Modeling

In this study, these matched test results from specimens exposed in a steady-state environment of 65°C and 75% RH for 60 or 160 da and from field-exposed specimens exposed for up to 3 yr in simulated roof structures in Mississippi (near Starkville, MS, in southeastern US) were then specifically analyzed for trends and quantitative relationships using nonparametric distributional analysis in which the mean and the 10th, 25th, 50th, 75th, and 90th percentiles of the bending strength distribution for each group were determined and then modeled. Modeling involved regression analysis of each group's unique set of mean and five percentile estimates. In this analysis, each group's predicted trend (ie slope) for each percentile–strength combination was modeled with time of exposure. Thus, for matched laboratory and field exposures, we obtained matched first-order estimates of strength trends (ie slope) with time via linear regression. Ratios of matched field-to-laboratory slopes for mean and at each of the five percentile levels were then averaged and used to develop comparative relationships for the differential rates of strength loss between cyclic seasonal, diurnal field exposures and steady-state, high-temperature laboratory exposures.

This approach placed slightly less emphasis on the central regions of the bending strength distributions and additional emphasis on the upper and lower regions for these strength distributions. We consider that such a modeling approach is appropriate because it is conservative in that it emphasizes both the lower regions that are critical in engineering design and the upper regions that are known to be affected more in past chemical-treatment effects literature reviews (Winandy 2001, 2013).

These field-to-laboratory relationships for Mississippi were then used to predict similar comparisons for a Wisconsin exposure modified using first-order kinetic relationships and previously reported roof sheathing temperature and exposure conditions obtained from matched Mississippi and Wisconsin locations (Winandy et al 2000).

RESULTS AND DISCUSSION

The results of the matched laboratory- and field-exposure specimens are given in Table 1. Also provided in Table 1 are results of a nonparametric (ie rank-order) analysis of the base data derived from testing these matched laboratory and field-exposure specimens. This analysis allowed calculation of a nonparametric distribution for each matched treatment–exposure group. A graphical representation of the strength loss data at the 25th, 50th, and 75th percentiles for untreated and MAP-treated plywood is given in Fig 1. By carefully inspecting the distributional data for the MPA and MPD treatments given in Table 1,

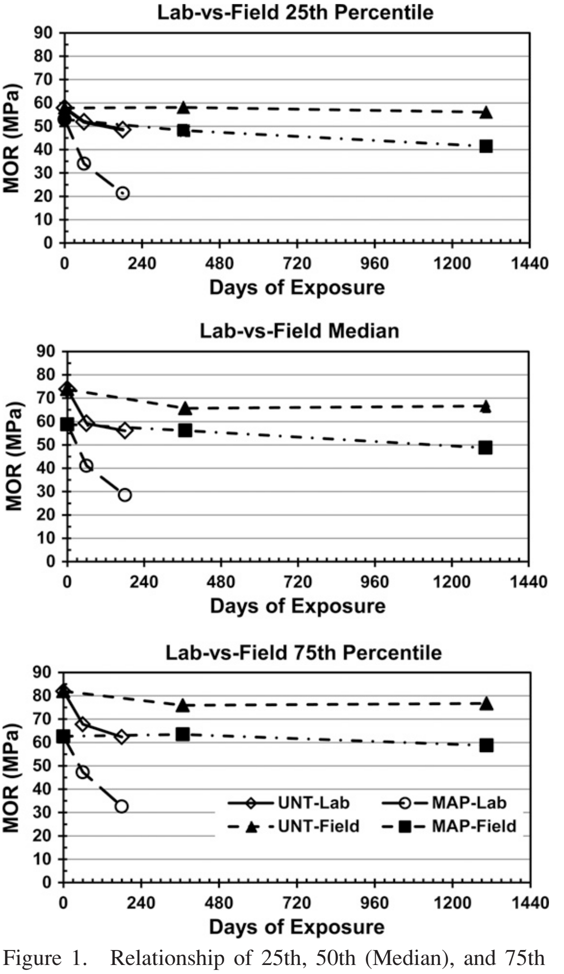

Figure 1. Relationship of 25th, 50th (Median), and 75th percentile modulus of rupture (MOR) values for matched untreated and monoammonium-phosphate-(MAP) treated plywood specimens exposed either in the laboratory at 65°C or in the field in simulated roof structures in Mississippi.

it is clear that these two treatments with only minor differences in magnitude of strength loss followed the same basic relationship as the untreated and the MAP-treated materials shown in Fig 1. This graphical analysis showed that there indeed appeared to be a basic linear relationship across most, if not all, of the bending strength distribution between matched plywood specimens exposed to a seasonally cyclic, diurnal field exposure and a steady-state laboratory exposure at 65°C and 75% RH.

Moisture content, specific gravity, MOE, and WML data for these laboratory- and field-exposure specimens were previously reported by Barnes et al (2010). The mechanical property data were not adjusted for moisture content because the three different treatments each tended to increase EMC by about 1-2%. This moisture content increase was a characteristic of the treatment, and any moisture-content-related adjustment would tend to mask either the treatment or in-service effect, or both.

Comparison of Field-to-Laboratory Exposures (Mississippi)

Both the nonparametric results of the matched laboratory- and field-exposure specimens were modeled by linear regression comparing matched test results and trends at the mean, 90th, 75th, 50th, 25th, and 10th percentiles (Table 2).

The results were then analyzed by treatment by conducting a traditional first-order regression analysis (eg $strength = b_o + b_1$ [*exposure time in days*]) for each of the five nonparametric percentile groupings of MOR for each treatment–exposure grouping. In such analysis, we assume the only difference in tested strength between the sets of matched plywood specimens is their respective field or laboratory exposure. We also assume that the graphical analysis previously mentioned verified, on a practical basis, that a general linear relationship between strength and exposure conditions existed. Given these assumptions, we can then average the six rate-of-strength loss estimates (ie the b_1 slope values) for each treatment–exposure condition. Next, the ratios of those averaged rate-of-strength loss estimates after matched field and laboratory exposures were then calculated and compared to develop an estimate of the basic time–temperature relationship between rate of strength loss in Mississippi field exposure when used as roof sheathing and rate of strength loss in steady-state laboratory exposure of 65°C and 75% RH.

Using these regression estimates of slope (ie rate of strength loss), the strength-loss relationship between laboratory and field exposure can be estimated for matched plywood samples. To accomplish this for each treatment or control, we calculated the ratio between the slope (b_1-average) value for field exposures and the corresponding slope (b_1-average) value derived for the laboratory exposures and use this ratio to predict the relationship between matched field and laboratory exposures (Tables 2 and 3).

Thus, for untreated plywood, 1 da of steady-state laboratory exposure at 65°C generally relates to about 26 da in a Mississippi simulated roof system. It also appears that for MAP-treated specimens, the relationship is 32 to 1 da. The rate of degrade in field exposure for both of the two FRT with added phosphoric acid (MPA at 25% added PA and MPD at 30% added PA) was more rapid than that of MAP (with no added PA). The MPA and MPD treatments with increased phosphoric acid loadings, regardless of if they were or were not supplemented with borates, tended to experience accelerated decrease in strength in field environments. Their field-to-laboratory exposure ratios of number of days in field exposure to days in steady-state 65°C laboratory exposure were 22:1 da for the MPA treatment and 18:1 da for the MPD treatment.

Although it might surprise many that the 32:1-da relationship for MAP is slower than the 26:1 relationship for untreated plywood, we were not surprised. Recall that previous work consistently showed that the initial effect of FRT on plywood strength ranged from –15 to –30%

Table 2. Regression analysis of nonparametric modulus of rupture (MOR) distributions found in Table 1 for matched untreated and MAP-, MPA-, and MPD-treated plywood exposed either in the laboratory at 65°C or in the field in simulated roof structures in Mississippi.[a]

	Laboratory exposure			Field exposure		
MOR (MPa)	Intercept (b_o)	Slope (b_1)	R^2	Intercept (b_o)	Slope (b_1)	R^2
Untreated						
Mean	67.33	−0.0766	0.76	69.08	−0.0031	0.65
90%	84.68	−0.1152	0.88	86.42	−0.0037	0.71
75%	78.68	−0.0999	0.82	79.89	−0.0031	0.39
50%	70.06	−0.0880	0.73	71.02	−0.0042	0.40
25%	56.60	−0.0482	0.88	58.17	−0.0015	0.86
10%	47.37	−0.0461	0.32	52.13	−0.0026	0.99
	b_1 average =	−0.0795	0.724	b_1 average =	−0.0030	0.67
				Field–laboratory b_1 ratio =	26.5	
MAP-treated						
Mean	53.47	−0.1560	0.92	56.91	−0.0050	0.99
90%	61.61	−0.1507	0.92	66.42	−0.0012	0.11
75%	60.33	−0.1604	0.96	63.48	−0.0034	0.81
50%	55.51	−0.1594	0.92	58.87	−0.0077	1.00
25%	49.33	−0.1658	0.91	52.27	−0.0085	0.98
10%	42.20	−0.1676	0.99	44.29	−0.0043	0.92
	b_1 average =	−0.1608	0.940	b_1 average =	−0.0050	0.76
				Field–laboratory b_1 ratio =	32.1	
MPA-treated						
Mean	52.05	−0.1652	0.92	54.63	−0.0078	0.96
90%	62.97	−0.1754	0.98	64.85	0.0001	0.33
75%	61.43	−0.1852	0.96	62.70	−0.0083	0.92
50%	52.75	−0.1734	0.85	55.64	−0.0108	0.88
25%	43.66	−0.1502	0.87	48.16	−0.0104	0.99
10%	38.62	−0.1420	0.92	39.56	−0.0072	0.79
	b_1 average =	−0.1652	0.916	b_1 average =	−0.0073	0.78
				Field–laboratory b_1 ratio =	22.6	
MPD-treated						
Mean	51.59	−0.1545	0.96	53.42	−0.0083	0.99
90%	66.58	−0.1759	0.97	69.11	−0.0084	1.00
75%	61.16	−0.1817	0.93	62.85	−0.0109	0.91
50%	50.85	−0.1410	0.98	52.85	−0.0071	0.98
25%	43.44	−0.1451	0.96	45.86	−0.0076	1.00
10%	39.41	−0.1504	0.91	40.31	−0.0093	0.82
	b_1 average =	−0.1588	0.947	b_1 average =	−0.0086	0.94
				Field–laboratory b_1 ratio =	18.5	

[a] MAP, monoammonium phosphate; MPA, 75% MAP and 25% phosphoric acid; MPD, 50% MAP, 30% phosphoric acid, and 20% disodium octaborate.

depending on treatment (Winandy 2001, 2013). In addition, virtually all previous work on FR effects showed that the rate of strength degrade slowed as strength properties diminished. Thus, because the MAP plywood started its laboratory and field exposures at about 80% of the strength of untreated plywood, the untreated laboratory-to-field strength loss relationship was slightly biased when applied to indirect comparisons rather than direct ones (eg comparing

Table 3. Comparative relationship for loss in plywood strength for matched laboratory- and field-exposed specimens.

Treatment[a]	Predicted ratio for plywood strength loss between Mississippi field exposure and a steady-state laboratory at 65°C/65% RH to achieve similar strength loss
UNT	26.5 to 1 da
MAP	32.1 to 1 da
MPA	22.6 to 1 da
MPD	18.5 to 1 da

[a] UNT, untreated; MAP, monoammonium phosphate; MPA, 75% MAP and 25% phosphoric acid; MPD, 50% MAP, 30% phosphoric acid, and 20% disodium octaborate.

untreated to MAP instead of $UNT_{initial}$ to UNT_{final} or $MAP_{initial}$ to MAP_{final}).

Comparison of Field-to-Laboratory Exposures (Mississippi to Wisconsin)

Using the predictive values given in Table 3, we can adjust those predictive values to other locations if adequate comparative data for localized exposure temperatures and time at temperature exist. One such directly comparative data set for plywood roof sheathing temperatures and time at temperature does exist. In that study, matched roof sheathing temperatures were recorded in nearly identical matched structures up to 3.5 yr in Mississippi and 8 yr in Wisconsin (Winandy et al 2000). Recognizing that the effects on strength of various generic FR chemical treatments were previously shown to be directly related to the kinetics of such systems (Lebow and Winandy 1999), these real-world, in-service roof sheathing temperatures allowed us to apply basic kinetic relationships to compare the field-to-laboratory exposure levels between two locations, Mississippi and Wisconsin.

A historically useful generalization supported by the Arrhenius relationship is that, for many first-order chemical reactions, the reaction rate (*ln k*) doubles for every 10°C increase in temperature (Zumdahl 1989). This "2× factor" relating first-order reaction rates to the influence of temperature on that reaction rate is often limited to reactions with activation energies (E_a) of 80-100 kJ/mol^{-1} (Alberty 1987). Lebow and Winandy (1999) derived E_a for MAP-treated and untreated wood and found that E_a ranged from 81 to 99 kJ/mol^{-1} for MAP and from 58 to 160 kJ/mol^{-1} for untreated depending on the first-order or nonlinear modeling approach used. Accordingly, because the derived E_a values for MAP, and to a lesser degree for untreated wood, fell in the E_a range of 80-100 kJ/mol^{-1}, we can apply first-order kinetic theory and assume that the reaction rate will double for each 10°C increase in temperature.

Thus, if we assume the reaction rate (*ln k*) is nearly 0.0 at 0°C, the kinetic rate-of-reaction factor will double for each hour it is exposed to a 10°C increase in temperature while in service.

The exposure severity factor for roof sheathing plywood exposed in Mississippi can be calculated by multiplying the number of hours of exposure at each 5°C exceedance temperature bin by the appropriate kinetic rate-of-reaction factor. An exceedance temperature bin is hereby defined as the total number of hours some particular roof element exceeded that temperature over some defined period of time (eg a year or a month), but did not reach the temperature of the next higher exceedance temperature bin. For example, an exceedance temperature bin could be from ≥5 to <10°C or from ≥20 to <25°C. Such a comparison is shown in Table 4. We can then use the Wisconsin exposure data to calculate an appropriate kinetic rate-of-reaction factor for that location. Then, by using the ratio of the Mississippi exposure severity factor to the Wisconsin factor, we can adjust the field-to-laboratory b_1 ratios derived in Table 2 for relating a Mississippi field exposure for each of the three FRT and untreated roof sheathing plywoods to develop a prediction of a field-to-laboratory b_1 ratio for a Wisconsin exposure (Table 5). Although the experimental laboratory- and field-exposure data from Mississippi predicted a field-to-laboratory exposure relationship of 18-26 to 1 for Mississippi, the derived model shown in Tables 4 and 5 predicted a field-to-laboratory exposure relationship of 64.0, 77.8, 55.0, or 44.8 to 1 da for Wisconsin for untreated or MAP-, MPA-, or MPD-treated plywood roof sheathing, respectively.

Table 4. Comparison of roof temperatures and hours of exposure at each 5°C temperature level between matched Mississippi and Wisconsin structures.

		Winandy et al (2000)			
		Table 2 t = time (h); T = Temp (°C)		Table 5 t = time (h); T = Temp (°C)	
Exceedance temperature[a] (°C)	Kinetic rate of reaction (*ln k*) factor	Wisc. (h)	t*T factor	Miss. (h)	t*T factor
0	0	1216	0	609	0
5	0.5	948	474	857	428.5
10	1	1003	1003	1043	1043
15	1.5	964	1446	1159	1738.5
20	2	652	1304	1398	2796
25	3	385	1155	641	1923
30	4	308	1232	421	1684
35	6	258	1548	355	2130
40	8	225	1800	348	2784
45	12	210	2520	338	4056
50	16	168	2688	284	4544
55	24	121	2904	310	7440
60	32	70	2240	272	8704
65	48	23	1104	194	9312
70	64	5	320	64	4096
75	96	0	0	2	192
80	128	0	0	0	0
Exposure severity factors		Sum (t*T) = 21,738		Sum (t*T) = 52,871	
Ratio of Mississippi-to-Wisconsin exposure severity factors (52,871/21,738) = 2.432					

[a] An exceedance temp of 5°C means hours of exposure to temperatures ≥5°C and <10°C.

It is critical that any user of such predictions involving either our field-to-laboratory relationships or relationships projected between different locations (such as Mississippi and Wisconsin) recognize that any such prediction and/or use of such predictions requires several assumptions and has certain limitations. We have attempted to be clear in stating those assumptions. However, based on our professional experience in conducting dozens of laboratory and/or field experiments for FRT and untreated wood, the predicted relationships presented in this study for both the field-to-laboratory relationships and relationships between different locations such as Mississippi and Wisconsin currently offer the best available science.

Table 5. Predicted relationship of number of days of exposure as roof sheathing in a Mississippi or Wisconsin structure to 1 da of steady-state laboratory exposure at 65°C and 65% RH.

Predicted Mississippi-to-Wisconsin field exposure factor for Mississippi data (in Table 3) times ratio of Mississippi–Wisconsin exposure severity factor (in Table 4)		
	Predicted relationship of days of exposure in the field to days in the laboratory	
Treatment[a]	Mississippi	Wisconsin
UNT	26.3	64.0
MAP	32.0	77.8
MPA	22.6	55.0
MPD	18.4	44.8

[a] UNT, untreated; MAP, monoammonium phosphate; MPA, 75% MAP and 25% phosphoric acid; MPD, 50% MAP, 30% phosphoric acid, and 20% disodium octaborate.

SUMMARY AND CONCLUSIONS

A series of matched plywood specimens were exposed to either laboratory or field exposures. Subsequent strength testing evaluated the quantitative relationships between field- and laboratory-exposure conditions as a function of exposure temperature and duration on the rate of change in strength of untreated and treated southern pine plywood. This study indicates that both untreated and MAP-treated plywood experienced strength loss with time when exposed at either a steady-state laboratory exposure of 65°C and 75% RH or when exposed in a Mississippi plywood roof system. Our models suggested that, in untreated plywood, 1 da of steady-state exposure at 65°C and 75% RH induced similar strength loss to 26 da in a Mississippi roof system when field exposure was averaged across 3.5 yr. For MAP-treated plywood, this same relationship was 1:32 da, respectively. Using actual roof temperature exposure data obtained in nearly identical structures in Mississippi and Wisconsin, we then derived comparable field-to-laboratory exposure factors for untreated and MAP-treated plywood exposed in these identical Wisconsin plywood roof systems. For a Wisconsin roof system, those comparative field-to-laboratory exposure factors came to about 64 to 1 for untreated plywood and 78 to 1 for MAP-treated plywood, respectively. We also discussed the many assumptions implicit in any use of these models, and users must recognize that any such predictions have significant limitations.

ACKNOWLEDGMENTS

This paper was approved as Journal Article FP741, Forest & Wildlife Research Center, Mississippi State University. This research was supported, in part, by USDA National Research Initiative, Competitive Grant for Natural Resources and the Environment, Grant No. 93–02444.

REFERENCES

Alberty RA (1987) Physical chemistry. 7th ed. John Wiley & Sons, New York, NY. 934 pp.

ASTM (2008a) D5516-03. Standard test method for evaluating the flexural properties of fire-retardant treated softwood plywood exposed to elevated temperatures. Annual Book of ASTM Standards, Vol. 4.10. American Society for Testing and Materials International, West Conshohocken, PA.

ASTM (2008b) D 5664-02. Standard test method for evaluating the effects of fire-retardant treatments and elevated temperatures on strength properties of fire-retardant treated lumber. Annual Book of ASTM Standards, Vol. 4.10. American Society for Testing and Materials International, West Conshohocken, PA.

ASTM (2008c) D 6305-02. Standard practice for calculating bending strength design adjustment factors for fire-retardant-treated plywood roof sheathing. Annual Book of ASTM Standards, Vol. 4.10. American Society for Testing and Materials International, West Conshohocken, PA.

ASTM (2008d) D 6841-03. Standard practice for calculating design value treatment adjustment factors for fire-retardant-treated lumber. Annual Book of ASTM Standards, Vol. 4.10. American Society for Testing and Materials International, West Conshohocken, PA.

Barnes HM, Winandy JE, McIntyre CR (2008) Laboratory and field exposures of FRT plywood: Part 1—Physical test data. Doc No IRG-WP 08-40426, Int Res Group on Wood Prot, Stockholm, Sweden.

Barnes HM, Winandy JE, McIntyre CR, Jones PD (2010) Laboratory and field exposures of FRT plywood: Part 2—Mechanical properties. Wood Fiber Sci 42(1):30-45.

Lebow PK, Winandy JE (1999) Verification of kinetics-based model for long-term effects of fire retardants on bending strength at elevated temperatures. Wood Fiber Sci 31(1):49-61.

LeVan SL, Kim JM, Nagel RJ, Evans JW (1996) Mechanical properties of fire-retardant-treated plywood after cyclic temperature exposure. Forest Prod J 46(5):64-71.

LeVan SL, Winandy JE (1990) Effects of fire retardant treatments on wood strength: A review. Wood Fiber Sci 22(1):113-131.

Winandy JE (1997) Effects of fire retardant retention, borate buffers, and redrying temperature after treatment on thermal-induced degradation. Forest Prod J 47(6):79-86.

Winandy JE (2001) Thermal degradation of fire-retardant-treated wood: Predicting residual service-life. Forest Prod J 51(2):47-54.

Winandy JE (2013) Effects of fire-retardant treatments on chemistry and engineering properties of wood. Wood Fiber Sci 45(2):131-148.

Winandy JE, Barnes HM, Hatfield CA (2000) Roof temperature histories in matched attics in Mississippi and Wisconsin. Res Pap FPL-RP-589. USDA For Serv Forest Prod Lab, Madison, WI. 24 pp.

Winandy JE, Lebow PK (2001) Modeling strength loss in wood by chemical composition. Part I. An individual component model for southern pine. Wood Fiber Sci 33(2):239-254.

Winandy JE, Levan SL, Ross RJ, Hoffman SP, McIntyre CR (1991) Thermal degradation of fire-retardant-treated plywood: Development and evaluation of a test protocol. Res Pap FPL-RP-501. USDA For Serv Forest Prod Lab, Madison, WI. 21 pp.

Zumdahl SS (1989) Chemistry. 2nd ed. D.C. Heath & Company, Lexington, MA. 1091 pp.