MECHANICAL PROPERTIES OF FIRE-RETARDANT-TREATED PLYWOOD AFTER CYCLIC TEMPERATURE EXPOSURE

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ABSTRACT

Some fire-retardant-treated (FRT) plywood used as roof sheathing has demonstrated loss of strength in service conditions. Research at the Forest Products Laboratory is aimed toward identifying the failure mechanisms of FRT wood, the chemicals that contribute to wood degradation, the temperature levels at which degradation occurs, the influence of moisture content (MC), and the correlation between these factors and the rate of degradation. To date, these efforts have led to the development of constant temperature test regimes for both plywood and lumber (ASTM D 5516-1994, and D 5664-1995, respectively). The objective of the research addressed here is the determination of how well constant temperature cycles relate to actual cyclic in-service temperature fluctuations. In this study, a special grade of southern pine plywood was treated with two fire-retardant chemicals and subjected to a cyclic temperature variation from room temperature to 65°C at two targeted MC levels, 6 and 12 percent. Results indicate that modulus of elasticity (MOE) and modulus of rupture (MOR) were relatively unchanged. The MOR values indicated a slight negative trend at both targeted MC levels, although the MOR values for the 12 percent specimens were slightly less than the MOR values for the 6 percent specimens. The most affected strength property was work to maximum load. The treated material showed a greater tendency for degrade than did the untreated material. In comparison with data from a plywood study using 65°C and 12 percent MC at constant temperature exposure, cyclic exposure appears to be less severe than constant temperature exposure. However, uncertainty regarding the internal temperature of the plywood could account for the difference in severity.

For certain applications, building codes and insurance companies permit fire-retardant-treated (FRT) wood to be used as an alternative to noncombustible materials. Fire retardants drastically decrease the rate at which flames travel across the wood surface, thereby reducing the capacity of the wood to contribute to a fire.

The use of some FRT plywood as roof sheathing has demonstrated a loss of strength in service. In the worst cases, roofs made with FRT plywood have required replacement. In these cases, the wood is usually darkened, is very brash and brittle, has low bending strength, and crumbles easily. For the severely degraded roofs brought to our attention, service time ranged from 3 to 8 years (6).

The magnitude of wood degradation depends on the particular fire-retardant formulation used, the temperature levels to which the material is exposed, and to a lesser extent, the presence of moisture. Research at the Forest Products Laboratory has been aimed toward identifying the failure mechanisms of FRT wood, the chemicals that contribute to wood degradation, the temperature levels at which degradation occurs, the influence of moisture content (MC), and the correlation between these factors and the rate of degradation (7,8).

Previous research results indicate that the influence of chemical treatment on strength properties is highly dependent on the thermal stability of the fire-retardant formulation. For clear southern pine wood treated with six generic chemicals (phosphoric acid, monoammonium phosphate, borax/boric acid, guanylurea phosphate/boric acid, dicyniamide/phosphoric acid/formaldehyde, and organophosphonate ester), no reduction in strength properties at 54°C was observed other than the initial treatment effect. At 82°C, all wood, including untreated controls, exhibited a reduction in strength (8). The magnitude of the reduction depended on the strength property tested. A companion study on plywood showed similar reductions of strength loss at 77°C and 65°C. In addition, the companion study showed that a 12 percent MC panel had slightly more degradation than did a 6 percent MC panel when evaluated at the same temperature (11). This plywood study used constant temperature and relative humidity conditions. To date, these efforts have led to the development of constant temperature test standards for both plywood and lumber, respectively (4,5). However, in reality, roof sheathing temperatures are not constant, and the

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Table 1.—Chemical retention levels.

Chemical	Average retention	Solution concentration
	(kg/m^3)	(% of weight)
MAP	55.5	8.14
GUP/B	55.5	8.19
Untreated	0	0

Table 2.—Targeted temperatures and relative humidities in environmental chambers.

Targeted MC	Time	Dry-bulb temperature	Wet-bulb temperature	Relative humidity
	(hr.)	(°C)	(°C)	(%)
6%	14	27	4	30
	8	65	45	42
12%	14	27	19	66
	8	65	57	77

influence of cyclic variations is unknown.

The objective of the research addressed here is the determination of how well constant temperature cycles relate to actual in-service temperature fluctuations. The goal of the cyclic exposure research was to determine if results significantly differ under varying temperature conditions. This paper outlines the experimental program and presents the results of the cyclic exposure at targeted 6 and 12 percent MC levels.

MATERIALS AND METHODS

PLYWOOD SPECIMENS

A special grade (N-grade) of defect-free, 15.9-mm-thick southern pine plywood was used. The plywood was a structural sheathing manufactured under performance standards meeting the PS 1-83 standard (10) and the American Plywood Association PRP-108 (1), bonded with adhesives qualified for exterior exposure. Specimens were cut into 0.15- by 0.61-m dimensions. To eliminate the effect of mechanical properties resulting from within- and between-panel variability differences, 1 specimen from each 1.22- by 2.44-m panel was assigned to 1 of the 32 groups. The order of specimens was alternated such that each group had the same number of specimens from each location in the plywood. Of the 32 groups, 10 groups were randomly selected for this study. There were 15 specimens in each of the 10 groups.

FIRE-RETARDANT TREATMENTS

Two fire-retardant treatments were used: guanylurea phosphate/boric acid (GUP/B) and monoammonium phosphate (MAP). The chemicals were pressure impregnated using a full-cell pressure process with 101-kPa vacuum for 30 minutes, followed by chemical addition with 1,034 kPa of pressure applied for 60 minutes. Concentration of the treating solution was adjusted to give aproximately 56-kg/m^3 retention **(Table 1).** One group was used for untreated controls.

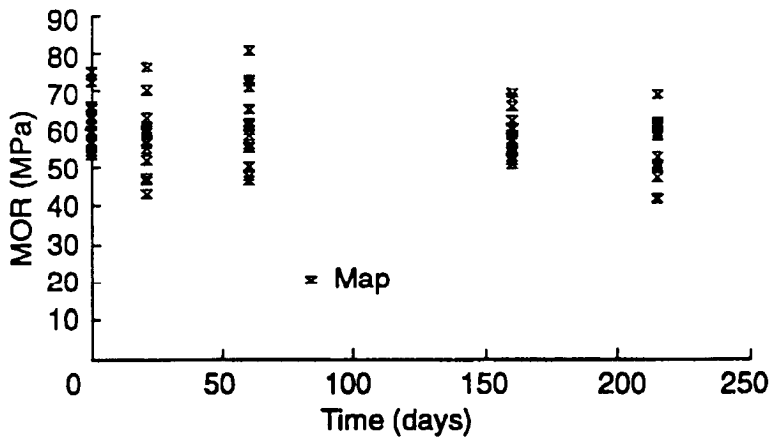

Figure 1 . — Modulus of rupture with exposure duration at 6 percent MC. All replicate data points are indicated.

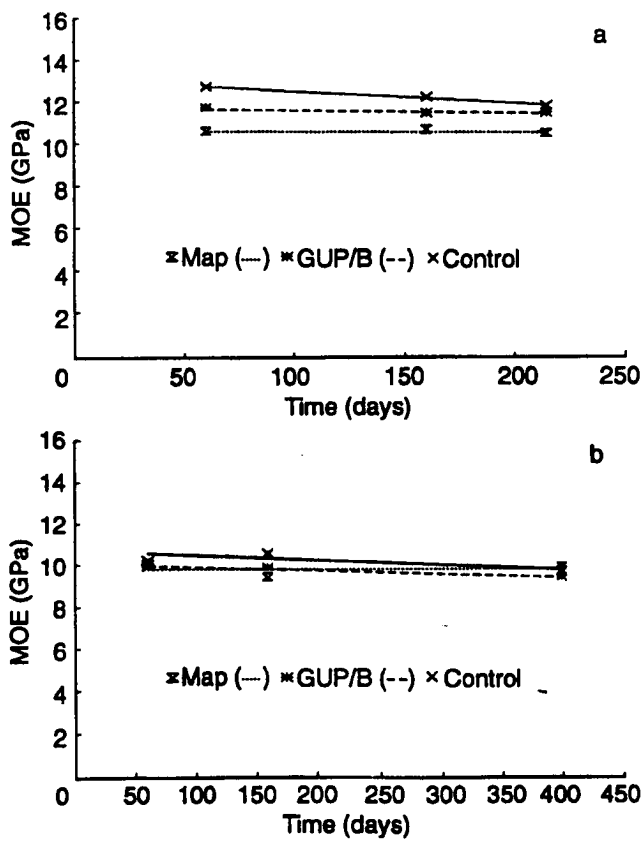

Figure 2. — Modulus of elasticity with exposure duration for two treated groups and one untreated group of specimens. Lines are from regression analysis; a. 6 percent MC; b. 12 percent MC.

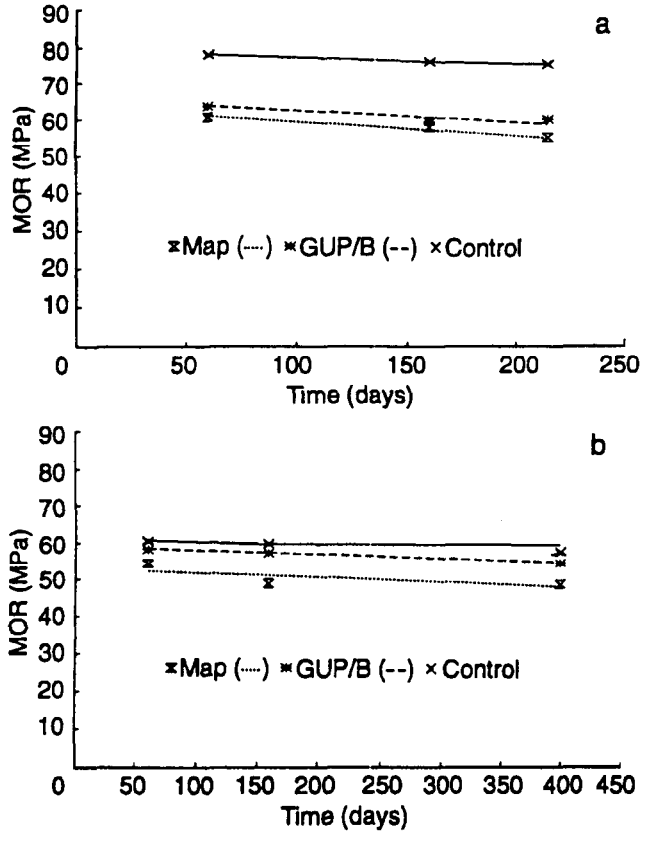

Figure 3. — Modulus of rupture with exposure duration for two treated groups and one untreated group of specimens. Lines are from regression analysis; a. 6 percent MC; b. 12 percent MC.

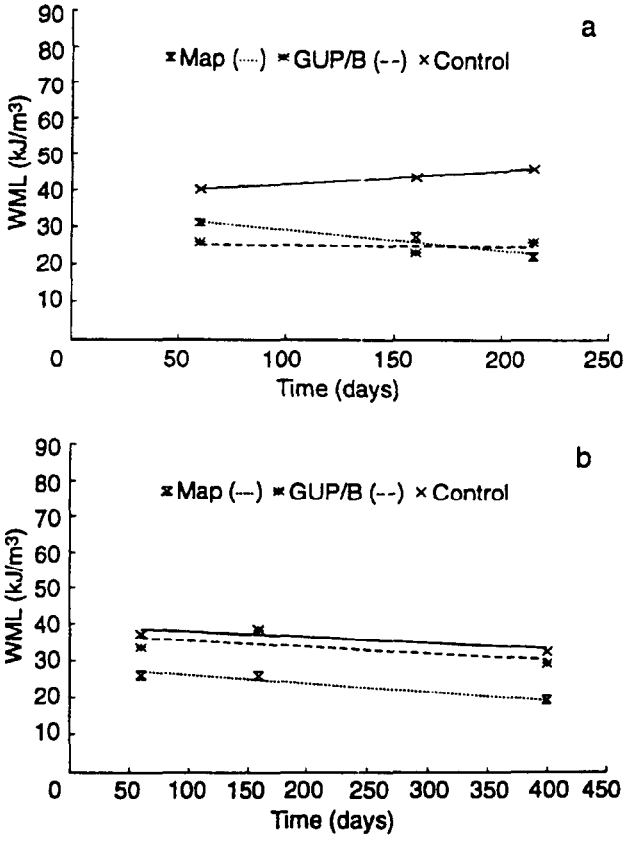

Figure 4. — Work to maximum load results exposure duration for two treated groups and one untreated group of specimens. Lines are from regression analysis; a. 6 percent MC; (b) 12 percent MC.

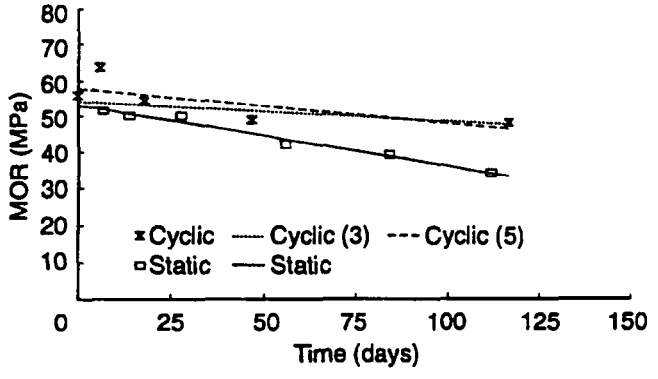

Figure 5.—Modulus of rupture with exposure duration at 65°C for MAP at 12 percent MC for both cyclic and constant temperature exposure. Lines are from regression analysis calculated using 7-hr./day **for cyclic exposure.**

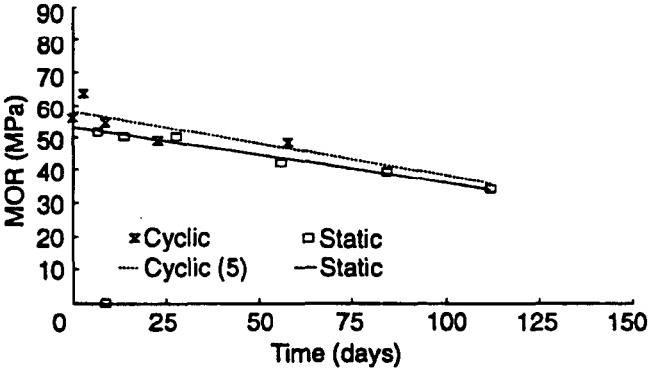

Figure 6. — Modulus of rupture with exposure duration at 65°C for MAP at 12 percent MC. Lines are from linear regression analysis calculated using 3.5-hr./cRy for cyclic exposure.

After treatment, the specimens were bundled in polyethylene and stored in a cold room until all specimens could be dried at the same time. The specimens were dried in a kiln using a relatively mild drying schedule. The dry-bulb temperature was held at 43°C for 9 days, and the wet-bulb temperature was held at 32°C for 9 days. After 9 days, the dry- and wet-bulb temperatures were changed to 49°C and 43°C, respectively, and allowed to complete the drying schedule for 7 days. After redrying, the 10 groups for each treatment were randomly assigned to each of the two targeted MC levels of 6 and 12 percent. This resulted in 5 groups of each treatment for each environmental chamber.

EXPOSURES

To investigate the effect of cyclic temperature exposures on the mechanical properties of wood, specimens were exposed to a 24-hour cycle consisting of 14 hours at 27°C, followed by 2 hours of ramping the temperature to 65°C, maintained at 65°C for 7 hours, then ramped down to 27°C for 1 hour. This constituted one cycle. We hoped this would approximate the temperature variations that plywood roof sheathing encounters in normal use. Relative humidity was adjusted in the environmental chamber at each temperature to achieve a targeted MC in the wood of approximately 6 percent in one chamber and 12 percent in the other chamber. **Table 2** gives the relative humidity values needed to maintain the targeted MC levels at the desired temperatures.

Fifteen replicates were used for each treatment, MC, and duration level. Duration times were 0, 21, 60, 160, and 215 days (cycles) for the 6 percent equilibrium MC and 0, 21, 60, 160, and 400 days (cycles) for the 12 percent equilibrium MC. After removal from the environmental chambers, specimens were weighed and reconditioned to constant weight at 23°C and 65 percent relative humidity (RH) prior to testing.

BENDING TESTS

After conditioning, treated and untreated specimens were tested in bending with face plies parallel to the span using the general procedures specified in ASTM D 3043-87, Method A (3). Deviations from the ASTM D 3043-87 standard were as follows:

Specimen size was nominal 0.15 by 0.61m.

Test span was 0.56 m.

End supports were rounded.

Load rate was 0.005 m/min.

Load and deflection data were continuously collected up to maximum bending load.

A yoke was not used.

Deflections were obtained from the bottom of the bending specimen.

The following properties were determined: modulus of elasticity (MOE), modulus of rupture (MOR), and work to maximum load (WML). W was calculated from bending results using the procedures outlined in ASTM D 1037-91 (2). Ovendry MC levels for all specimens were determined after the bending tests.

RESULTS

Mechanical property results after the cyclic temperature exposure can be used to determine the relative effect of different fire-retardant chemicals and various MC levels. The effect of fire-retardant chemicals was determined by comparing the data for MOE, MOR, and WML between the chemicals at each MC level. **Figure 1** illustrates the complete MOR data set at 6 percent MC. The effect of MC was determined by comparing each fire-retardant chemical at both 6 and 12 percent MC levels **(Figs. 2** to **4).** Mechanical properties after cyclic temperature exposure are given in **Table 3.** The cyclic data at 12 percent MC were then compared with data from the study (11) in which plywood was exposed to a constant temperature of 65°C with 12 percent MC **(Figs. 5** and **6).**

6 PERCENT MC

MODULUS OF ELASTICITY

The MOE values appeared to be relatively constant during exposure and followed a ranking order, with MAP having the lowest and the untreated control the highest. The ranking order of the chemical effect was consistent with the constant exposures reported by LeVan et al. (8). Analysis of variance (ANOVA) indicated a statistically significant MOE difference between treatments (at the 0.0001 level of testing) and a significant MOE difference for the duration of exposure (0.0001). The ANOVA was followed with a Tukey student.ized range test to determine which differences were statistically different. Results can be summarized using an underline notation where we write down the treatments in order of increasing mean values and underline with a common line the means that are not statistically different at the 0.05 level of testing. For this analysis of MOE values, the results were as follows:

Treatment effects:	MAP	GUP/B	Control
Means:	10.4	11.1	11.7

Duration of exposure:	0	21	215	160	60
Means:	10.4	10.6	11.3	11.4	11.7

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These results indicate that each of the treatment means is significantly different from all the other treatment means. The duration of exposure results indicate that the 0- and 21-day exposures were not significantly different at the 5 percent confidence level. Also, data from the 60-, 160-, and 215-day exposures were not significantly different. In addition, the 21- and 215-day exposures were not statistically dtierent,

MODULUS OF RUPTURE

The ANOVA for MOR indicated a significant treatment and duration of exposure interaction (0.0151), meaning that the effect of treatment depends upon the duration of exposure and the effect of duration of exposure depends upon the treatment. To understand this interaction, an ANOVA was used to test the effect of duration of exposure for each treatment and then an ANOVA was used to test the effect of treament for each duration of exposure. The results of the ANOVAs and Tukey tests when the ANOVA was significant can again be summarized using the underline notation:

Treatment	Duration of exposure				
GUP/B	0	160	215	60	21
	59.6	59.7	60.2	63.8	64.5
MAP	215	21	160	60	0
	55.4	57.3	58.1	60.8	62.2
Control	21	0	215	160	60
	64.8	72.8	75.5	76.5	78.3

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Exposure	Treatment		
0	GUP/B	MAP	Control
	59.6	62.2	72.8
21	MAP	GUP/B	Control
	57.3	64.5	64.8
60	MAP	GUP/B	Control
	60.8	63.8	78.3
160	MAP	GUP/B	Control
	58.1	59.7	76.5
215	MAP	GUP/B	Control
	55.4	60.2	75.5

Generally, the specimens showed a 15 to 20 percent MOR reduction compared with the untreated controls. Figure 1 shows the MOR data for each MAP specimen. The variability in the data for the GUP/B treatment and the control is similar to that in Figure 1. In addition, MOE and WML showed the same variability between specimens.

WORK TO MAXIMUM LOAD

As with MOR, the ANOVA for WML indicated a significant treatment and duration of exposure interaction (0.0192), meaning again that the effect of treatment depends upon the duration of exposure and the effect of duration of exposure depends upon the treatment. An ANOVA followed by a Tukey test of means was used to test the effect of duration of exposure for each treatment and then to test the effect of treament for each duration of exposure. The results of these tests can also be summarized using the underline notation:

Treatment	Duration of exposure				
GUP/B	160	215	60	0	21
	23.37	25.99	26.10	31.31	32.25
MAP	215	160	21	60	0
	22.18	27.43	28.52	31.13	37.17
Control	21	60	0	160	215
	34.90	40.25	42.21	43.71	45.89

Exposure	Treatment		
0	GUP/B	MAP	Control
	31.31	37.17	42.21
21	MAP	GUP/B	Control
	28.52	32.25	34.90
60	GUP/B	MAP	Control
	26.10	31.13	40.25
160	GUP/B	MAP	Control
	23.37	27.43	43.71
215	MAP	GUP/B	Control
	22.18	25.99	45.89

12 PERCENT MC

MODULUS OF ELASTICITY

The ANOVA for MOR indicated a significant treatment and duration of exposure interaction (0.0345). The results of an ANOVA followed by a Tukey multiple-comparison test were used to test the effect of duration of exposure for each treatment and then to test the effect of treament for each duration of exposure. The results of these tests can be summarized using the following underline notation:

Treatment	Duration of exposure				
GUP/B	400	160	60	0	21
	9.4	9.9	9.9	11.3	12.3
MAP	160	400	60	0	21
	9.4	9.9	10.1	11.1	12.5
Control	400	60	160	0	21
	9.7	10.3	10.6	13.4	13.7

Exposure	Treatment		
0	MAP	GUP/B	Control
	11.1	11.3	13.4
21	GUP/B	MAP	Control
	12.3	12.5	13.7
60	GUP/B	MAP	Control
	9.9	10.1	10.3
160	MAP	GUP/B	Control
	9.4	9.9	10.6
400	GUP/B	Control	MAP
	9.4	9.7	9.9

MODULUS OF RUPTURE

The ANOVA for MOR indicated a significant treatment and duration of exposure interaction (0.0009). The results of the follow-up ANOVAs and Tukey-multiple comparison tests can be summarized as follows using underline notation:

Treatment	Duration of exposure				
GUP/B	400	160	60	21	0
	54.1	57.5	58.6	63.7	64.8
MAP	400	160	60	0	21
	48.3	48.9	54.4	56.0	63.7
Control	400	160	60	21	0
	57.3	59.9	60.8	69.4	79.0

Exposure	Treatment		
0	MAP	GUP/B	Control
	56.0	64.8	79.0
21	MAP	GUP/B	Control
	63.7	63.7	69.4
60	MAP	GUP/B	Control
	54.4	58.6	60.8
160	MAP	GUP/B	Control
	48.9	57.5	59.9
400	MAP	GUP/B	Control
	48.3	54.1	57.3

WORK TO MAXIMUM LOAD

The ANOVA indicated a significant treatment effect (0.0001) and a significant duration of exposure effect (0.0018). A Tukey multiple-comparison test to compare the treatment mean effects and the duration of exposure mean effects showed the following significance:

Treatment effects:	MAP	GUP/B	Control
Means:	25.72	32.74	36.99

Duration of exposure:	400	60	21	0	160
Means:	26.81	32.30	32.68	33.06	34.23

The WML values of the MAP specimens, the GUP/B specimens, and the untreated controls were all significantly different from each other **(Fig. 4).** The WML values of the MAP specimens were approximately 25 to 30 percent less than those of the untreated controls. The WML values of the GUP/B specimens were approximately 10 to 20 percent less than those of the untreated controls.

COMPARISON OF 6 AND 12 PERCENT SPECIMENS

With the exception of WML at 12 percent, the ANOVA indicated no significant difference in the strength values for the last three exposure times, partly as a result of the large variability introduced in the 0- and 21-day data. However, trends were observed in the last three time points, which was consistent with previous research. Therefore, we examined the trends using data from 60 days and beyond. A possible explanation in the data variability early in the analysis could be related to differential MC levels **(Table 4),** which are discussed later in this article. Thus, Figures 2 to 4 include only the data from 60, 160, and 215 days for the 6 percent MC specimens and 60, 160, and 400 days for the 12 percent MC specimens.

For both treatments and the untreated control, MOE curves indicated no difference between the slopes at either the 6 or 12 percent levels (Fig. 2). However, the intercepts were significantly different between the treated and the untreated specimens for the 6 percent specimens. For the 12 percent specimens, there was no significant difference in the MOE curves.

For both treatments and the untreated control, MOR data indicated no difference in slopes between the 6 and 12 percent specimens **(Fig. 3).** However, the intercepts were significantly different between the treated and untreated specimens at 6 percent MC and between the untreated specimens and the MAP speci-

Table 3.—Mechanical properties of FRT plywood after cyclic exposure.

Treatment	Exposure	Density			MOE			MOR			WML		
		Mean	SD	COV	Mean	SD	COV	Mean	SD	COV	Mean	SD	COV
	(days)	(kg/m^3)			(GPa)			(MPa)			(kJ/m^3)		
6% MC													
MAP	0	649.2	25.3	3.9	10.2	1.3	12.6	62.2	6.0	9.6	37.17	11.97	32
	21	645.0	28.9	4.5	10.0	1.1	11.4	57.3	8.4	14.7	28.52	10.88	38
	60	657.7	28.5	4.3	10.6	1.4	13.3	60.8	9.6	15.8	31.13	8.89	29
	160	643.8	30.3	4.7	10.7	1.2	11.1	58.1	5.8	10.0	27.43	7.06	26
	215	651.6	29.9	4.6	10.5	1.2	11.8	55.4	7.7	13.9	22.18	8.29	37
GUP/B	0	641.8	28.4	4.4	10.1	1.4	13.7	59.6	10.6	17.8	31.31	12.92	41
	21	640.2	29.2	4.6	11.0	1.7	15.2	64.5	11.8	18.4	32.25	13.31	41
	60	649.4	27.6	4.3	11.7	1.6	13.8	63.8	11.2	17.6	26.10	8.90	34
	160	632.9	28.8	4.5	11.4	1.1	9.8	59.7	7.7	12.8	23.36	6.13	26
	215	633.4	23.1	3.6	11.5	0.9	7.7	60.2	9.2	15.3	25.99	9.57	37
Untreated	0	624.2	37.6	6.0	11.0	1.6	14.2	72.8	9.5	13.0	42.21	13.12	31
	21	619.3	41.5	6.7	10.9	1.6	14.6	64.8	13.1	20.2	34.90	16.77	48
	60	628.9	30.8	4.9	12.7	1.0	8.1	78.3	11.6	14.8	40.25	12.79	32
	160	625.2	34.1	5.5	12.2	1.7	14.1	76.5	12.3	16.1	43.71	17.64	40
	215	628.4	34.3	5.5	11.8	1.8	15.0	75.5	12.5	16.6	45.89	20.51	45
12% MC													
MAP	0	637.0	22.6	3.6	11.1	1.2	11.0	56.0	9.7	17.3	26.09	9.89	38
	21	664.5	25.2	3.8	12.5	1.4	10.8	63.7	7.5	11.8	31.51	8.66	27
	60	640.6	24.0	3.8	10.1	1.0	10.4	54.4	6.4	11.8	26.02	7.56	29
	160	615.4	21.4	3.5	9.4	1.0	10.4	48.9	5.3	10.9	25.77	7.53	29
	400	602.0	30.5	5.1	9.9	1.5	15.3	48.3	8.4	17.3	19.22	7.05	37
GUP/B	0	643.3	24.7	3.8	11.3	1.2	10.6	64.8	7.5	11.6	32.52	7.44	23
	21	662.8	18.4	2.8	12.3	1.6	13.3	63.7	9.4	14.7	30.23	7.74	26
	60	623.4	24.7	4.0	9.9	1.1	11.3	58.6	5.6	9.6	33.60	6.24	19
	160	625.4	25.9	4.1	9.9	1.3	13.0	57.5	8.2	14.3	38.40	15.00	38
	400	586.7	31.4	5.4	9.4	1.5	15.5	54.1	9.4	17.3	28.94	11.89	41
Untreated	0	626.6	35.4	5.6	13.4	1.9	14.3	79.0	9.6	12.2	40.57	9.50	23
	21	633.0	31.4	5.0	13.7	2.2	16.2	69.4	8.0	11.5	36.30	8.30	23
	60	601.9	18.7	3.1	10.3	1.5	15.0	60.8	6.5	10.8	37.29	5.80	16
	160	602.0	23.6	3.9	10.6	1.3	11.8	59.9	9.1	15.2	38.52	10.27	27
	400	589.9	31.4	5.3	9.7	2.1	21.8	57.3	12.0	20.9	32.26	11.61	36

mens at 12 percent. In addition, the MOR values from the l2 percent specimens were slightly less than those from the 6 percent specimens.

The WML slopes of the MAP specimens were significantly different from the control specimens at 6 percent MC, but there were no differences in slopes between the treatments and untreated controls at 12 percent MC **(Fig. 4).** In fact, controls from the 6 percent specimens appeared to increase with exposure duration. The only explanations for this apparent difference are that some unknown experimental differences occurred or not enough data points existed to establish the regression with sufficient accuracy. For solid wood, the effect of MC on WML is expected to be "erratic." However, for a chemical degradation caused by an acidic environment, we expected increased MC levels to accelerate the degradation. The WML values from the 6 and 12 percent MC specimens did not exhibit such behavior. Closer examination of the influence of MC showed that, in general, the MOE, MOR, and WML values for the 12 percent specimens for both treatments were usually less than those values of the 6 percent specimens, with the slopes being about equal but with different intercepts. Only the WML values of the untreated controls exhibited an unexpected anomaly. The WML values indicated different slopes between the 6 and 12 percent specimens. The slope for the 6 percent specimens was slightly positive, and the slope for the 12 percent specimens was slightly negative.

A partial explanation for the differences between the untreated specimens at 6 and 12 percent MC can be found in the data shown in **Table 4.** The MC data were obtained after the specimens had been re-equilibrated to equilibrium conditions obtained at 25°C and 76 percent RH. These conditions have also been shown to achieve an equilibrium MC of 12 percent in Sitka spruce. Data showed hat the untreated controls exposed at a 6 percent targeted MC re-equilibrated to an average of 9.5 percent MC and the untreated controls at the 12 percent target re-equilibrated to an average of 13.0 percent MC. However, plywood is known to equilibrate at 2 to 3 percent less than wood (9). The O-time controls at both 6 and 12 percent showed equilibrations to 9.5 percent MC. These specimens were exposed to 25°C and 76 percent RH. Thus, the controls at 12 percent showed some increase in their capability to re-equilibrate to a higher MC level. This was probably caused by moisture hysteresis. The MC levels of the two treatment groups had a smaller percentage difference between the 6 and 12 per-

Table 4.—MC of specimens after bending tests.

Treatment	Exposure	MC Mean	MC Standard deviation	MC Coefficient of variation
6% MC	(days)	- - - - - - - - (%) - - - - - - - -		
MAP	0	13.5	0.05	0.4
	21	11.5	0.15	1.3
	60	11.3	0.35	3.1
	160	10.7	0.44	4.1
	215	11.0	0.41	3.7
GUP/B	0	12.7	0.09	0.7
	21	11.1	0.31	2.8
	60	10.8	0.23	2.1
	160	10.9	0.45	4.1
	215	11.3	0.73	6.5
Untreated	0	9.7	0.26	2.7
	21	9.3	0.17	1.8
	60	9.4	0.20	2.1
	160	9.7	0.46	4.7
	215	9.6	0.33	3.4
12% MC				
MAP	0	13.4	0.12	0.9
	21	14.1	0.11	0.8
	60	14.5	0.12	0.8
	160	15.2	0.29	1.9
	400	13.7	0.20	1.5
GUP/B	0	12.6	0.08	0.6
	21	13.5	0.07	0.5
	60	13.9	0.31	2.2
	160	14.6	0.28	1.9
	400	13.4	0.15	1.1
Untreated	0	9.7	0.20	2.1
	21	13.7	0.10	0.7
	60	13.8	0.57	4.1
	160	14.5	0.21	1.4
	400	13.5	0.15	1.1

Table 5.—Comparison of cyclic temperature with constant temperature.

Specimens	MOR slope: Cyclic at 65°C[a] 7-hr./day	MOR slope: Cyclic at 65°C[a] 3.5 hr./day	MOR slope: Constant at 65°C
MAP	–0.097	–0.194	–0.171
Untreated	–0.043	–0.086	–0.002

[a] Slope from regression line using all data points.

cent specimens than did the untreated controls.

Therefore, the difference between relative humidity at 6 and 12 percent MC at 65°C under cyclic conditions appeared to have a relatively small effect on the mechanical properties of FRT plywood.

DISCUSSION

Previous data indicate little difference between the 6 and 12 percent MC specimens at elevated cyclic temperatures on the effect of strength properties of southern pine plywood. Similar results were found by LeVan and Collet (6) with small, clear wood specimens. In addition, the cyclic data suggest little difference between the two chemical treatments, MAP and GUP/B. Such results are different from the study of LeVan et al. others (8) on clear wood at a constant temperature of 65°C. One apparent reason for this difference could be the reduced exposure severity provided by the cyclic exposure when compared to the constant temperature exposure.

To evaluate whether cyclic exposure is less severe for a given length of time at a particular temperature than is a constant temperature for the same length of time, we compared cyclic data from this study with the constant temperature study by Wlnandy et al. (11). The only differences between these two studies were the specimen width and exposure. The cyclic study used 152-mm-wide specimens, and the constant temperature study used 75-mm-wide specimens. Both studies used the same grade and cutting patterns.

The exposure times for the cyclic temperature data had to be calculated in times representing the total time at 65°C for a 7-hr./day cycle, thus the time point representing 400 days is actually 117 days at 65°C. **Figure 5** gives the MOR values for the cyclic and constant temperature exposures. In addition, **Figure 5** shows the cyclic data for the regression line using all five data points and the regression line using the data points from 60 days and beyond. **Table 5** gives the slopes of these lines. The constant temperature exposure had a slope of-0.171 MPa per day. The cyclic exposure using all five data points had a slope of -0.097 MPa per day.

In contrast, the untreated data do not show the same trend. The slope of the untreated cyclic exposure using all five data points is 0.043 MPa per day, and the untreated constant temperature exposure has a slope of 0.002 MPa per day. However, the untreated data are probably indicative that at 65°C, elevated temperatures cause almost no decrease in strength properties. The minor differences between the cyclic slope and the constant temperature slope are probably due to variability in the data.

Thus, the data indicate that the cyclic exposure is less severe than the constant temperature exposure. However, this implies some other chemical mechanism other than the one proposed by LeVan et al. (8). An obvious question is: What is the temperature profile in the plywood specimens? The cyclic exposure data were recalculated, assuming that the interior temperature of the plywood was 65°C for 3.5 hours instead of 7 hours. **Figure 6** shows the cyclic temperature (using all five data points) and the constant temperature assuming 3.5 hours per cycle at 65°C. With the cyclic data calculated using the 3.5-hour assumption, the MAP slopes are almost identical **(Table 5).** To clarify this issue, additional data are needed to establish the temperature

profile in the plywood specimens. When the correct temperature profile in the specimens is known, then the comparison with the constant temperature exposures can be established. Thus, the apparent difference in severity of exposures between cyclic and constant temperatures can be explained by inaccurate estimation of the thermal loading on the plywood specimens.

We anticipated that the effect of cyclic exposure on the strength properties of FRT plywood would be greater than the results indicated in this study. Such an anticipation assumes that the MAP treatment approximates the commercial product and furthermore that the drying condition simulates drying for commercial products. In fact, the drying conditions used for this study were considerably milder than commercial drying practices. The selected cyclic exposure chosen in this study is much more severe than would occur in reality because cloud cover can reduce the incident radiation. However, this study indicates the difficulty in conducting cyclic exposure research and the need for monitoring the temperature within the plywood specimens or using some other measurement system to monitor or calculate the internal temperature profile.

Conclusions

Results indicate that cyclic temperature exposures ranging from ambient to 65°C have minimal effect on strength properties after approximately a 1-year exposure. Mechanical properties were influenced more by the type of fire-retardant chemical than exposure duration. Results indicate that the MOE values were relatively unchanged during exposure. The MOE values for the targeted 12 percent MC specimens were only slightly less than those of the targeted 6 percent MC specimens. The MOR values had a slight negative trend during exposure, but the trend was not statistically different for the two treatments; the MOR values for 12 percent specimens were only slightly less than the MOR values for 6 percent specimens. The most affected strength property was WML. Treated material showed a greater tendency for degrade than did untreated material. A comparison of cyclic exposure data with data from a constant temperature exposure study indicates that cyclic exposure is less severe. However, uncertainty regarding the actual time the plywood spent at 65°C casts doubts on the accuracy of such a comparison.

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