THE ROLE OF GRADE AND THICKNESS IN THE DEGRADATION OF FIRE-RETARDANT-TREATED PLYWOOD

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ABSTRACT

In some cases, fire-retardant-treated plywood used since 1980 for roof sheathing has rapidly degraded and failed, apparently because of thermally induced acid hydrolysis. This study sought to determine whether plywood grade or thickness influences the manner in which fire-retardant treatment (FRT) and subsequent high-temperature exposure affects the strength properties of plywood. The effects of FRT were evaluated on two thicknesses and three commercial grades of southern pine plywood as well as plywood constructed from nearly defect-free N-grade veneer. Specimens were treated with monoammonium phosphate (MAP), then subjected to exposure at 66°C (150°F) and 75 percent relative humidity for either 30, 60, or 90 days. Modulus of rupture (MOR), work to maximum load (WML), and modulus of elasticity (MOE) of the specimens were evaluated. Results suggest that the rate of plywood degrade resulting from FRT, redrying, and subsequent high-temperature exposure is largely independent of plywood quality or grade. Although the initial strength loss caused by FRT and redrying appeared greater for the thinner plywood, degrade during subsequent temperature exposure appeared to be independent of plywood thickness. Thus, it appears that findings from previous studies on thermal degrade using high quality, N-grade plywood are readily applicable to commercial grades and thicknesses. Evaluation of the effects of knots and voids on MOR revealed that these defects are only partially responsible for the difference in bending strength among specimens.

Since 1980, fire-retardant-treated plywood has been used for roof sheathing in many commercial and multifamily dwellings that were built in the eastern United States. In most applications, this plywood has been performing well. In some cases, however, this treated sheathing has rapidly degraded and failed within 1 to 8 years of installation (1,4). The nature and extent of these failures were reported previously by the National Association of Home Builders (4).

The severity and economic repercussions of these failures led to a series of research studies to investigate the cause. This research indicated that the combination of the acid fire-retardant chemicals used in some formulations and the high temperature and moisture conditions found in some roofs caused acid hydrolysis of wood components (3,5,9). Subsequently, research was conducted to clarify the role of solution formulation, treatment and re-drying practices, and exposure conditions on degradation of fire-retardant-treated plywood in an effort to develop methods of evaluating the serviceability of roof sheathing in service (6-8). However, many of these studies were conducted with a special N-grade of plywood, which is nearly defect free. Additional information is needed to adapt this database to field applications. The study reported herein addresses that need, with the objective of determining whether plywood grade or thickness influences the manner in which fire-retardant treatment (FRT) and subsequent high-temperature exposure affects the strength properties of plywood.

MATERIALS AND METHODS

SPECIMEN PREPARATION

The effects of FRT were evaluated on 13- and 19-mm- (1/2- and 3/4-in.-) thick southern pine plywood. The commercial grades A-C Exterior, C-C Exterior, and C-D Exposure were evaluated for both thicknesses **(Table 1).** In addition, 13-mm (1/2-in.) plywood (4 ply) was constructed from nearly defect-free N-grade veneers using exterior glue. Used in previous studies, N-grade veneer reduces variation in mechanical properties resulting from random placement of defects in interior veneers. Five sheets of 1.2- by 2.4-m (4- by 8-ft.) southern pine plywood were utilized for each grade and thickness combination. Each 1.2- by 2.4-m (4- by 8-ft.) sheet was cut to obtain 32 specimens with a width of 152 mm (6 in.) and a length of 610 mm (24 in.) (parallel to the face grain). Four of the 32 specimens obtained from each sheet were randomly assigned to 1 of 8 experimental groups (2 treatments, 4 exposures), providing 20 replicates **(Table 1).** Prior to treatment, all specimens were uniformly conditioned to approximately 12 percent moisture content (MC) in a room main-

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tained at 23°C (74°F) and 65 percent relative humidity (RH).

FIRE-RETARDANT TREATMENT

The four groups of each grade and plywood thickness were pressure treated with monoammonium phosphate (MAP), using a 30-minute vacuum (-85 kPa (25 in.Hg)), followed by 60 minutes of pressure (860 kPa (125 psi)). The two plywood thicknesses were treated in separate charges, with the solution concentration adjusted to achieve a retention of approximately 56 kg/m^3 (3.5 pcf) MAP. An equal number of specimens were set aside to serve as untreated controls. The MAP-treated specimens were subsequently kiln-dried to approximately 15 or 19 percent MC for the 13- and 19-mm (1/2- and 3/4-in.) thicknesses, respectively. The drying temperature was 71°C (160°F) with a 54°C (130°F) wet-bulb temperature for either 20.5 hours (13-mm-thick plywood) or 29 hours (19-mm-thick plywood). Following kiln-drying, the specimens were reconditioned to constant weight in a room maintained at 23°C (74°F), 65 percent RH.

HIGH-TEMPERATURE EXPOSURE

The MAP-treated and untreated specimens were subjected to high-temperature exposure in a room maintained at 66°C (150°F) and 75 percent RH for either 30, 60, or 90 days. Following the designated exposure, the specimens were allowed to re-equilibrate to constant weight in a room maintained at 23°C (74°F), 65 percent RH. These conditions produce an approximate equilibrium MC of 12 percent in untreated lumber. One group of treated and untreated specimens of each grade and thickness combination was maintained at 23°C (74°F) and 65 percent RH to serve as controls for the effects of high-temperature exposure.

MECHANICAL TESTING

Each 152- by 610-mm (6- by 24-in.) plywood specimen was tested in bending using center-point loading (2). The inferior face of each specimen was oriented downward during testing to maximize tensile stresses in the lowest quality face veneer. Load and center-span deflection data were digitally recorded. Modulus of elasticity (MOE), modulus of rupture (MOR), and work to maximum load (WML) values were calculated.

DEFECT ESTIMATION

Following mechanical testing, a cross section of each specimen was cut from adjacent to the zone of failure, and the width of knots or voids in each ply was measured. An I-ratio was developed as a method to quantify the volume of defects in the cross section and account for the greater importance of defects in the outer ply. The l-ratio adjusts the moment of inertia (I) for voids or knots within the critical cross section (at failure) as measured over l-mm increments across the 152-mm-wide specimen and by each individual veneer thickness (i.e., 5 ply: $j = h/5$):

$$I_{unadjusted}(bh^3)/12 = \sum_{i=0}^{b}\sum_{j=0}^{h} A_{ij} d_j^{\,2} \qquad [1]$$

$$I_{adjusted} = \sum_{i=0}^{b}\sum_{j=0}^{h} (A_{ij} q_{ij}) d_j^{\,2} \qquad [2]$$

$$I-ratio = I_{adjusted}/I_{unadjusted} \qquad [3]$$

where:

A_{ij} = unit area for each i,j

d_i = distance from neutral axis for each i,j

q_{ij} = quality parameter (1 if wood, 0 if knot or void) for each i,j

b = width (152 mm)

i = unit width (1 mm)

h = height (thickness)

j = unit height (i.e., veneer thickness).

All bending failures occurred within 25.4 mm (1 in.) of the center-point load.

STATISTICAL ANALYSIS

Prior to statistical analysis, values of residual MOR, MOE, and WML were calculated for each specimen. Residual values were calculated as the ratio of the bending value of the specimen to the average of the bending values for the respective untreated, unexposed control group. For example, residual MOR values for MAP-treated, 13-mm- (1/2-in.-) thick, N-grade specimens exposed at 66°C (150°F) for 30, 60, or 90 days were obtained by dividing the MOR value of each specimen by the average of the MOR values of the untreated, 13-mm- (1/2-in.-) thick N-grade specimens that had not been exposed to high temperatures. Using the residual values, the results were analyzed as a three-factor factorial split-plot, with grade and thickness as whole-plot factors and treatment type as a subplot factor. A generalized linear model procedure was then used to determine if grade, thickness, or treatment had an effect on strength properties. Because this analysis revealed interaction between grade and thickness, the two thicknesses were then analyzed separately as two-factor split-plot designs.

RESULTS AND DISCUSSION

INITIAL STRENGTH PROPERTIES

Plywood grade was not always a good indicator of the original strength properties of the plywood. In some cases, poorer grades of plywood had greater untreated strength than did superior grades (see 0-day exposure means, **Table 2).** As expected, within the 13-mm (1/2-in.) plywood, the N-grade specimens were greater in MOR, MOE, and WML than in the other grades, reflecting the defect-free veneers used to construct these panels. However, the 13-mm (1/2-in.) C-C Exterior grade specimens exceeded the A-C Exterior exposure specimens in original MOR, MOE, and WML. The A-C Exterior and C-D Exposure grades performed similarly in the bending tests, suggesting that the strength of this particular batch of A-C Exterior plywood was less than might be expected compared with the other grades.

TABLE 1 — Design of study to evaluate the interactive effects of FRT, thickness, grade and high-temperature exposure on plywood bending properties. Each treatment group had 20 replicates.

Plywood grade	Thickness	FRT Treatment[a]	Exposure to 66°C (150°F), 75% RH
	(mm(in.))		(days)
N-Grade	13 (0.5)	MAP,[a] and no treatment	0, 30, 60, and 90
A-C Exterior	13 (0.5)	MAP, and no treatment	0, 30, 60, and 90
	19 (0.75)		
C-C Exterior	13 (0.5)	MAP, and no treatment	0, 30, 60, and 90
	19 (0.75)		
C-D Exposure	13 (0.5)	MAP, and no treatment	0, 30, 60, and 90

[a] MAP is monoammonium phosphate.

TABLE 2. — Average MOR, MOE, and WML values and average I-ratio values for each treatment group

Grade	FRT	Days	Unadjusted means MOR		MOE		WML		Mean I-ratio	Mean I-ratio adjusted MOR[b]
13-mm specimens			(MPa)		(MPa)		(kJ/m^3)			
N-Grade	MAP	0	57.9	(8.2)[a]	10,988	(1984)	30.2	(10.1)	1.000	58.0
N-Grade	MAP	30	45.6	(6.7)	9976	(1516)	17.4	(8.6)	1.000	45.6
N-Grade	MAP	60	39.6	(8.6)	10,347	(2494)	10.6	(3.9)	0.998	39.7
N-Grade	MAP	90	33.8	(8.8)	9730	(2033)	7.7	(3.1)	1.000	33.8
N-Grade	Control	0	70.5	(9.5)	11,825	(2584)	41.0	(15.5)	1.000	70.6
N-Grade	Control	30	61.5	(10.5)	10,519	(1860)	35.8	(14.2)	0.989	62.3
N-Grade	Control	60	58.3	(8.2)	10,976	(1778)	28.1	(14.4)	1.000	58.3
N-Grade	Control	90	60.8	(8.7)	11,110	(2239)	34.9	(14.7)	1.000	60.8
A-C Exterior	MAP	0	39.9	(8.0)	7972	(1474)	19.2	(9.8)	0.962	41.3
A-C Exterior	MAP	30	31.9	(7.9)	7483	(1447)	11.9	(7.6)	0.978	32.3
A-C Exterior	MAP	60	26.2	(8.2)	7907	(1488)	6.4	(3.2)	0.986	26.2
A-C Exterior	MAP	90	22.8	(6.9)	7560	(1178)	4.8	(2.5)	0.975	23.4
A-C Exterior	Control	0	49.8	(11.2)	8810	(1557)	21.6	(11.7)	0.982	50.6
A-C Exterior	Control	30	44.0	(10.7)	7945	(1220)	24.4	(12.8)	0.972	45.0
A-C Exterior	Control	60	48.5	(8.5)	8720	(1468)	24.6	(10.1)	0.992	48.8
A-C Exterior	Control	90	42.9	(8.9)	8430	(1709)	21.8	(12.6)	0.989	43.4
C-C Exterior	MAP	0	46.5	(12.3)	9551	(2432)	21.2	(12.7)	0.973	46.9
C-C Exterior	MAP	30	38.6	(11.4)	9351	(1447)	14.7	(10.1)	0.987	39.0
C-C Exterior	MAP	60	31.4	(10.2)	8771	(2356)	9.1	(7.0)	0.987	31.7
C-C Exterior	MAP	90	28.8	(9.7)	9013	(2136)	7.1	(4.1)	0.975	29.5
C-C Exterior	Control	0	61.2	(10.5)	11,259	(1757)	30.9	(13.2)	0.982	62.0
C-C Exterior	Control	30	55.4	(5.5)	10,338	(1571)	29.9	(11.6)	0.988	56.3
C-C Exterior	Control	60	55.5	(7.8)	9995	(1461)	27.7	(13.0)	0.989	56.0
C-C Exterior	Control	90	50.4	(13.3)	9804	(2439)	27.0	(15.0)	0.979	50.8
C-D Exposure	MAP	0	39.6	(8.8)	7951	(1323)	20.0	(11.0)	0.849	47.0
C-D Exposure	MAP	30	27.5	(7.3)	6993	(1433)	8.6	(4.3)	0.925	29.6
C-D Exposure	MAP	60	23.1	(5.8)	6890	(1454)	6.3	(4.1)	0.890	25.9
C-D Exposure	MAP	90	22.4	(7.0)	7179	(1385)	5.4	(3.0)	0.909	24.4
C-D Exposure	Control	0	48.2	(11.6)	9191	(1826)	29.4	(12.5)	0.886	54.4
C-D Exposure	Control	30	44.0	(10.9)	7827	(1516)	21.9	(9.5)	0.927	47.3
C-D Exposure	Control	60	43.2	(8.1)	8027	(1564)	23.3	(9.6)	0.904	48.2
C-D Exposure	Control	90	44.1	(9.5)	8185	(1564)	23.2	(9.9)	0.904	48.5
A-C Exterior	MAP	0	44.1	(9.8)	7650	(1626)	24.3	(9.0)	0.912	47.9
A-C Exterior	MAP	30	30.8	(9.0)	7454	(1592)	10.1	(6.2)	0.910	34.9
A-C Exterior	MAP	60	27.5	(7.0)	7560	(1454)	7.5	(7.6)	0.948	30.3
A-C Exterior	MAP	90	23.5	(8.3)	6998	(1523)	5.8	(7.4)	0.940	26.2
A-C Exterior	Control	0	48.9	(10.3)	8444	(1716)	23.4	(10.9)	0.905	55.1
A-C Exterior	Control	30	47.9	(9.8)	8423	(1337)	28.2	(14.7)	0.918	55.8
A-C Exterior	Control	60	51.2	(11.4)	8589	(1488)	30.3	(15.9)	0.916	53.5
A-C Exterior	Control	90	46.9	(8.5)	7790	(1240)	26.7	(11.8)	0.979	48.0
C-C Exterior	MAP	0	39.6	(6.6)	7727	(854)	17.7	(8.0)	0.955	41.9
C-C Exterior	MAP	30	30.4	(7.4)	7856	(1412)	9.4	(4.1)	0.965	31.7
C-C Exterior	MAP	60	22.9	(4.8)	7200	(841)	5.8	(1.9)	0.963	23.8
C-C Exterior	MAP	90	21.8	(5.2)	7428	(1027)	5.0	(1.8)	0.954	23.1
C-C Exterior	Control	0	50.3	(12.2)	8579	(1261)	28.0	(14.7)	0.962	52.3
C-C Exterior	Control	30	47.4	(8.7)	8449	(1474)	25.4	(10.7)	0.933	51.1
C-C Exterior	Control	60	47.2	(10.1)	8616	(1364)	23.9	(13.7)	0.950	50.0
C-C Exterior	Control	90	44.5	(10.5)	8280	(1357)	21.5	(10.6)	0.916	49.7
C-D Exposure	MAP	0	33.9	(8.8)	6339	(1502)	15.7	(6.9)	0.926	37.0
C-D Exposure	MAP	30	24.7	(6.0)	6073	(1337)	7.1	(2.1)	0.915	27.1
C-D Exposure	MAP	60	19.7	(5.8)	5599	(1392)	4.8	(2.1)	0.946	20.8
C-D Exposure	MAP	90	19.6	(5.3)	5593	(1461)	4.8	(1.7)	0.905	21.9

Continued on next page

TABLE 2. — Continued from previous page.

C-D Exposure	Control	0	39.3	(10.6)	6714	(1660)	20.0	(9.5)	0.942	41.7
C-D Exposure	Control	30	38.8	(9.6)	6583	(1392)	20.1	(8.1)	0.926	42.4
C-D Exposure	Control	60	36.4	(9.1)	6294	(1605)	18.8	(9.1)	0.941	38.8
C-D Exposure	Control	90	35.1	(8.6)	6060	(1406)	16.7	(6.5)	0.957	36.7

[a] Values in parentheses are standard deviations for individual treatment groups.

[b] Mean of the individual adjusted MORs in the treatment group. $I-ratio\ adjusted = \left[\sum_{i=1}^{n}\left(\frac{MOR_i}{I-ratio_i}\right)/n\right]$

where:
n = specimens/group; MOR = unadjusted MOR for each specimen; and I-$ratio$ is from Equation [3] for each i.

An examination of the I-ratios (a measure of defect size, **Table 2**) for the 13-mm (1/2-in.) plywood grades revealed that the C-C and A-C grades had similar amounts of defect, and the C-D Exposure grade had a greater proportion of defects. This finding suggests that the relatively poor performance of the A-C Exterior grade specimens was not entirely caused by the presence of knots or voids. Instead, it may have been a function of other parameters, such as deviations in grain angle (i.e., diving grain), which were not specifically controlled in this study.

Within the 19-mm (3/4-in.) plywood specimens, the A-C and C-C Exterior grades had similar initial bending properties, and the bending properties of the C-D Exposure grade specimens were much lower. However, this difference was not reflected in the I-ratios of the respective grades **(Table 2),** because all three grades had similar volumes of defects. Again, it would appear that other factors, such as grain angle, contributed to the differences in the initial mechanical properties of the three veneer grades.

INITIAL PRESSURE TREATMENT AND REDRYING EFFECTS

For each grade and plywood thickness, strength loss occurred during MAP pressure treatment and subsequent redrying of the panels **(Table 2, Figs. 1** and **2).** It is probable that much of this loss was caused by wetting and redrying and would have occurred with a water solution containing no MAP. Statistical analysis revealed no significant difference ($\alpha = 0.05$) in the relative pressure treatment effect between the plywood grades for either thickness, meaning that all grades were similarly affected by pressure treatment and redrying.

There was an observable difference in the initial effect of pressure treatment and redrying on the mechanical properties of the two plywood thicknesses. Across all plywood grades, the 13- and 19-mm (1/2- and 3/4-in.) specimens suffered average decreases of 18 and 14 percent, respectively, in MOR, and 25 and 18 percent, respectively, in WML, after pressure treatment and redrying. MOE was the least affected property, suffering a loss of 11 percent in the 13-mm (1/2-in.) plywood and 8 percent in the 19-mm (3/4-in.) plywood. Based on these results, it would seem that any pressure treatment and redrying effect was dependent on the plywood thickness under consideration and differentiation in the design adjustment process may be warranted.

HIGH TEMPERATURE EXPOSURE EFFECT

Plywood grade. — Exposure to conditions of 66°C (150°F) and 75 percent RH caused a reduction in mechanical properties for all grades and treatment groups **(Figs. 1** and **2).** However, statistical analysis revealed that for both thicknesses (except for one case) there was no significant difference ($\alpha = 0.05$) in the way the different grades of plywood were affected. The one exception occurred in residual WML for the untreated 19-mm (3/4-in.) plywood. As shown in **Figure 2C,** the residual WML for the untreated A-C Exterior grade plywood is substantially greater than that of the C-D Exposure and C-C Exterior grade plywoods during the high-temperature exposure. However, only the difference between the A-C and C-C Exterior grades was statistically significant at the 95 percent confidence level. This difference appears to be an artifact of the low mean WML at O-day exposure for the untreated A-C Exterior grade plywood. However, it is interesting that a similar, although not statistically significant, trend occurred for the untreated 13-mm (1/2-in.) A-C Exterior plywood **(Fig. 1C).** This phenomenon does not appear to be primarily a function of plywood grade or quality, because the untreated 13-mm (1/2-in.) N-grade plywood, which is virtually defect-free, did suffer reductions in WML during high-temperature exposure. In addition, the amount of defect in the A-C Exterior grade specimens, as measured by the I-ratio **(Table 2),** was similar to that of the C-C Exterior grade specimens for both plywood thicknesses.

Among the MAP-treated specimens, the different plywood grades experienced similar levels of thermally induced degradation in mechanical properties. Despite a large difference in absolute values of the mechanical properties in the various grades, all suffered strength loss at approximately the same rate. For all MAP-treated groups, regardless of grade, the largest reduction in MOR and WML occurred within the first 30 days of exposure. There was a slight tendency for the specimens that were least affected by the initial treatment and redrying (i.e., slightly higher residual values at 0-day exposure) to suffer greater losses in MOR and WML during the first 30 days of high-temperature exposure, ultimately reaching residual strength values similar to the other grades. However, these differences were not statistically significant. After 90 days of high-temperature exposure, the MAP-treated specimens had suffered approximately 50 percent reduction in residual MOR and 80 percent reduction in WML. As with the original treatment effects, WML was the property most dramatically affected by high-temperature exposure. Overall reductions in MOE were less dramatic, but reductions were significant after 60 days of exposure for both plywood thicknesses. The untreated specimens also suffered significant strength losses, although to a much lesser degree than the MAP-treated groups.

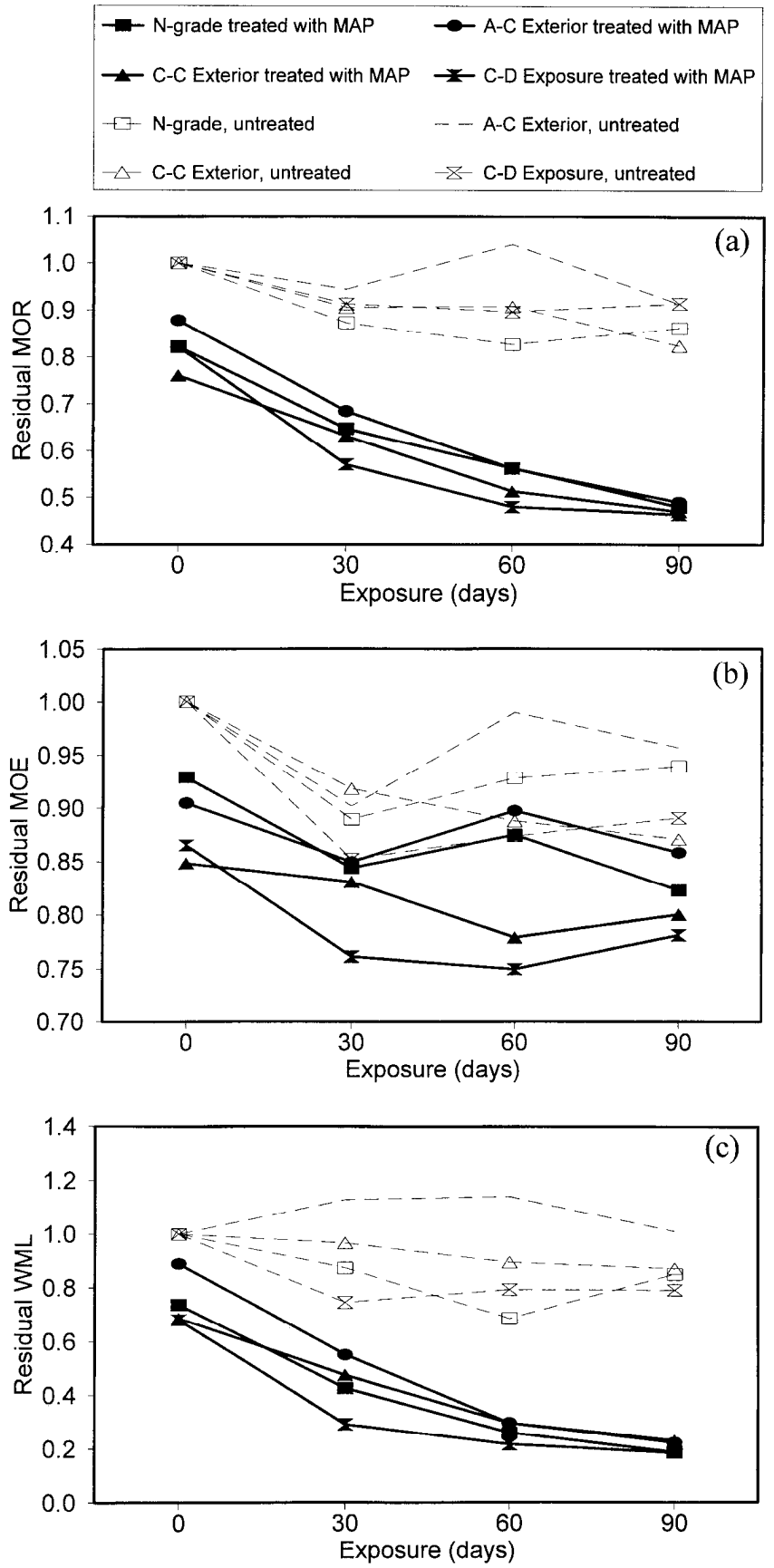

Figure 1. — Effect of MAP treatment and high-temperature exposure on average residual (a) MOR, (b) MOE, and (c) WML for four grades of 13-mm (1/2-in.) specimens.

Recent studies of FRT effects on clear wood and N-grade plywood also reported that WML was the property most affected by high-temperature exposure, and elastic properties (MOE) were the least affected (3,6,7,9).

Plywood thickness. — Although interaction prevented direct statistical comparison, high-temperature exposure appeared to have similar effects on the strength properties of both the 13- and 19-mm (1/2- and 3/4-in.) plywood. The 13-mm (1/2-in.) MAP-treated plywood appeared to suffer slightly greater degradation during the first 30 days of high-temperature exposure. After 90 days of high-temperature exposure, however, the residual values of MOR, MOE, and WML for the two thicknesses were almost identical when compared across all plywood grades. This finding agrees with a recent study that found little difference in the effect of FRT and subsequent high-temperature exposure on the rate of degrade of two thicknesses of N-grade plywood (7).

Influence of defects

Although the rates of thermal-induced degrade were similar for all four grades of 13-mm- (1/2-in.-) thick plywood and three grades of 19-mm- (3/4-in.-) thick plywood, we also wanted to address the influence of quality (e.g., size and placement of knots, voids, gaps in the veneers) for each specimen within each group-time combination. To adjust for differences in plywood quality, we divided the MOR value of each specimen by its I-ratio parameter (Eq. **[2]**). Statistical analysis of these adjusted means revealed no significant difference ($\alpha = 0.05$) between the rate of thermal degrade (i.e., the slopes), among the grades of 13-mm- (1/2-in-) thick plywood **(Fig. 3),** or the grades of 19-mm- (3/4-m.-) thick plywood **(Fig. 4).** Although adjustment for defects further reduced differences between the slope of degrade curves for the various grades, it was apparent that there were still differences in absolute MOR between some of the grades at individual time points. Therefore, two conclusions seem warranted. First, the rates of thermal degrade between various grades of plywood are similar. Thus, the rate of one grade can apparently be used to estimate the rate of other grades. Second, the unresolved difference between adjusted (for I-ratio) MOR values implies that although differential defect level is a sig-

nificant co-contributor, I-ratio alone does not fully explain the inherent strength of various specimens. As would reasonably be expected, other parameters, such as slope of grain, could also be used to account for differences in strength between specimens.

CONCLUSIONS

The results of this study suggest that the rate of plywood degrade resulting from FRT, redrying, and subsequent high-temperature exposure are largely independent of plywood quality or grade. Although the various grades of plywood had large absolute differences in MOR, MOE, and WML values, these differences remained relatively constant after treatment and exposure. Even though the initial treatment effect differed for the two plywood thicknesses tested, the relative loss in strength resulting from exposure at high temperatures was similar for both plywood thicknesses studied. Thus, it appears that findings from previous studies on thermal degrade using high quality, N-grade plywood are readily applicable to commercial grades and thicknesses. In the study reported herein, evaluation of the effects of knots and voids on MOR revealed that these defects are only partially responsible for differences in bending strength between specimens.

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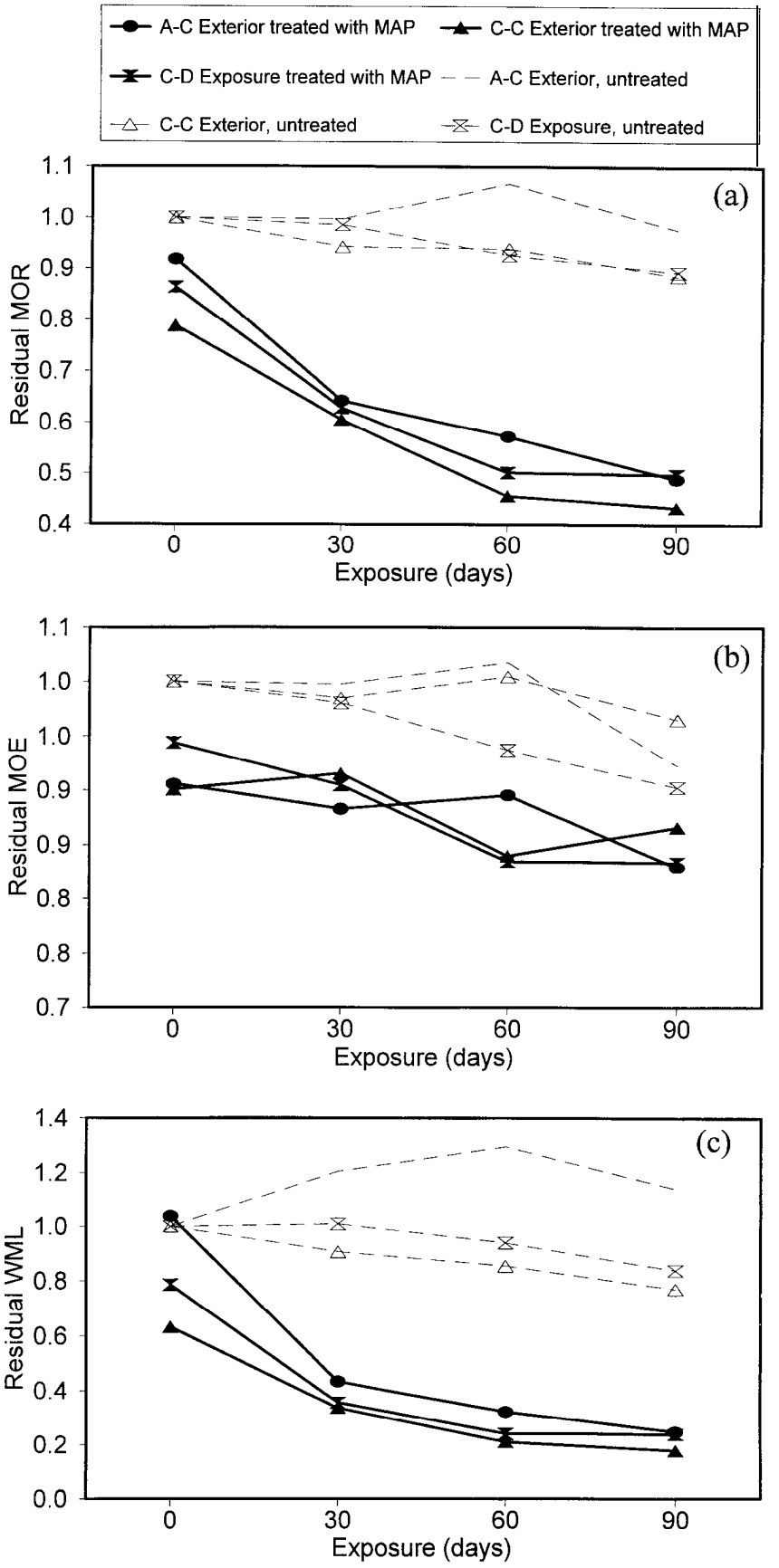

Figure 2. — Effect of MAP treatment and high-temperature exposure on average residual (a) MOR, (b) MOE, and (c) WML for three grades of 19-mm (3/4-in.) specimens.

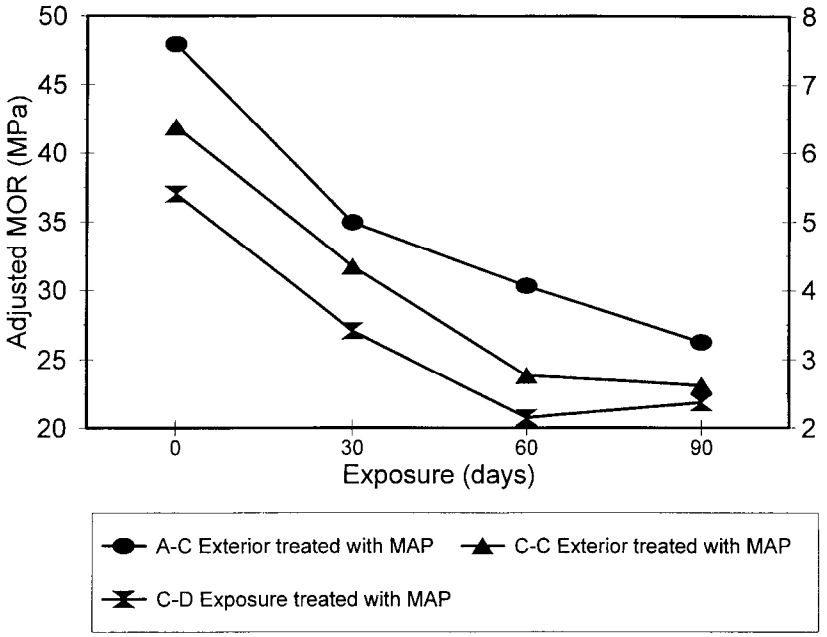

Figure 3. — Effect of MAP treatment and high-temperature exposure on average MOR for four grades of 13-mm (1/2-b.) specimens after adjustment for volume of defect in each specimen.

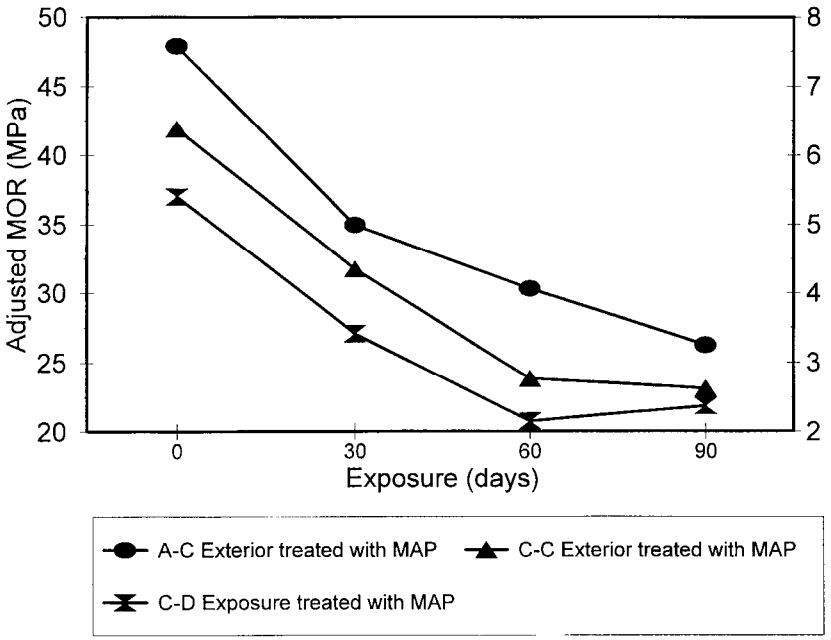

Figure 4. — Effect of MAP treatment and high-temperature exposure on average MOR for three grades of 19-mm (3/4-in.) specimens after adjustment for volume of defect in each specimen.

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