THERMAL DEGRADATION OF FIRE-RETARDANT-TREATED WOOD: PREDICTING RESIDUAL SERVICE LIFE

JERROLD E. WINANDY*

ABSTRACT

This paper presents a review of more than 10 years of research on the effects of tire-retardant treatments on wood properties and the potential of these treatments for in-service degradation when exposed to elevated temperatures. It presents an in-depth discussion of the findings and implications of a major wood engineering research program to assess the current condition, extend service life, and predict residual serviceability of fire-retardant-treated plywood when used as structural roof sheathing.

Wood is an environmentally desirable material for fiber and structural use. It is efficient in both economic and environmental costs to the user. Sometimes wood is treated with chemicals to extend its utility into new markets. In North America, fire-retardant-treated plywood is sometimes permitted as an alternative to noncombustible materials in structures that require increased fire safety. However, in the mid-to-late 1980s some commercial fire-retardant (FR) treatments failed to perform as expected when used as roof sheathing plywood and roof truss lumber. Elevated roof temperatures caused by solar radiation in combination with FR chemicals and moisture prematurely activated some FRs, often causing the plywood to exhibit a darker brown color, become brittle, experience cross-grain checking, and crumble easily. This problem required costly roof replacement. Because of the regional nature of building codes in North America, the problem was most common in the eastern United States on nonresidential commercial and multifamily dwellings built without parapet walls since 1980. In the United States, replacement costs for thermally degraded FR-treated plywood roof sheathing were originally estimated to exceed $2 billion ($U.S.) (15). However, current estimates range from 25 to 50 percent of the earlier projected cost.

During the last few years, extensive research has defined the mechanism of the problem. To lessen the economic and environmental costs of replacing up to 75 million FR-treated plywood panels, serviceability assessment methods were needed to evaluate the condition of FR-treated plywood and to estimate residual service life. An intensive 10-year research program was conducted at the USDA Forest Products Laboratory (FPL) in which methodologies were developed to determine the current condition of FR-treated plywood roof sheathing and to predict its residual serviceability. Two of these experimental methodologies that assessed the effects of FR treatments on mechanical properties and their potential to undergo thermal degradation on extended exposure to elevated temperatures resulted in two new ASTM Standard Test Methods (ASTM D 5516 and D 5664) (1). A standard practice for deriving adjustment factors for FR-treated plywood was also developed (ASTM D 6305 (1). To preclude future serviceability problems with the use of FR-treated wood in engineered wood systems, these new ASTM test methods and design practices have been incorporated as mandatory performance requirements in AWPA Standard P17 for FR formulations and in Standards C20 and C27 for FR-treated lumber and plywood, respectively (2).

The author is Team Leader, USDA Forest Serv., Forest Prod. Lab., One Gifford Pinchot Dr., Madison, WI 53705-2398. The author acknowledges the indispensable contributions of the staff of the Engineering Mechanics Lab. at the Forest Prod. Lab. (FPL) and of the entire FR-treated plywood serviceability team at FPL, which consists of Stan T. Lebow, Patricia K. Lebow, Joseph F. Murphy, William Nelson, Anton TenWolde, and Robert H. White. Past members of that team were Susan L. LeVan, Robert J. Ross, and Mitchell S. Sweet. We acknowledge the financial assistance of the Dept. of Community Affairs (State of New Jersey) and the USDA Competitive Grants Program. We also gratefully acknowledge the work of our extramural cooperators: H. Michael Barnes (Mississippi State Univ.), William Rose (Univ. of Illinois), Elmer L. Schmidt (Univ. of Minnesota), Craig R. McIntyre (Consultant), and Scott P. Hoffman (Hickson Corp.). This paper was received for publication in February 2000. Reprint No. 9095.
*Forest Products Society Member.

Forest Prod. J. 51(2):47-54.

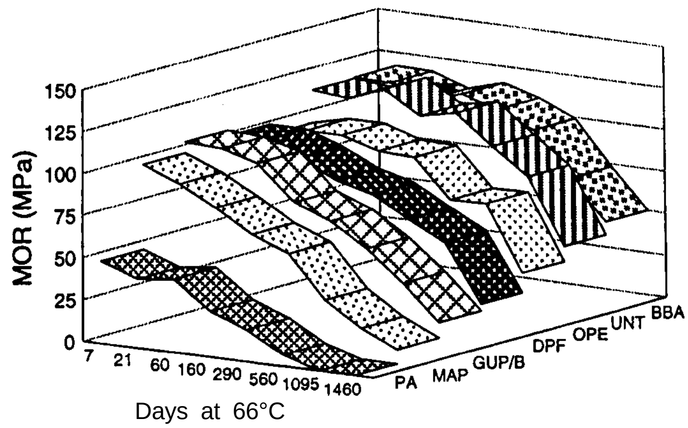

Figure 1. — Predicted change in bending strength over steady-state exposure of up to 4 years at 66°C for untreated (UNT) wood and wood treated with phosphoric acid (PA), monoammonium phosphate (MAP), guanylurea phosphate/boric acid (GUP/B), dicyandiamide-phosphoric acid-formaldehyde (DPF), organophosphonate ester (OPE), or borax/boric acid (BBA).

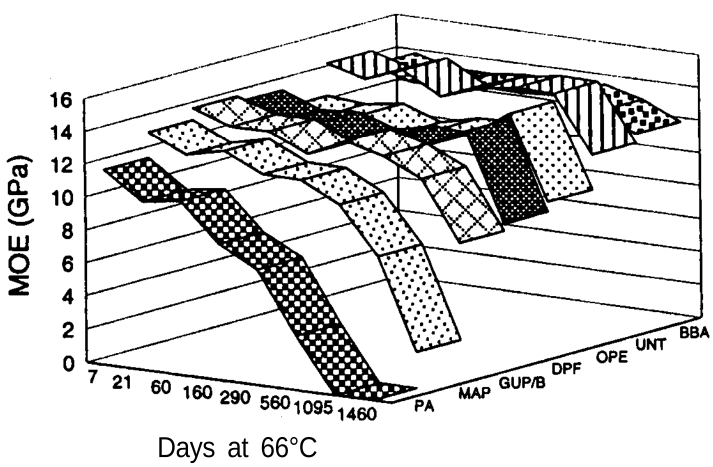

Figure 2. — Predicted change in modulus of elasticity (MOE) over steady-state exposure of up to 4 years at 66°C for untreated and treated wood.

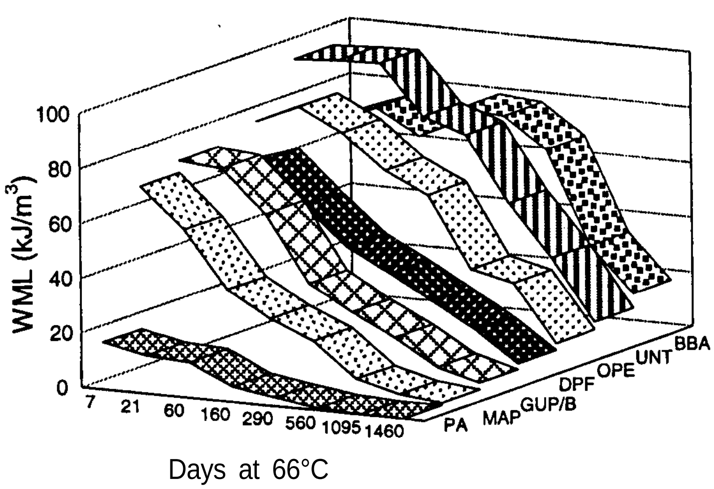

Figure 3.— Predicted change in work to maximum load (WML) over steady-state exposure of up to 4 years at 66°C for untreated and treated wood.

The FPL research program involved two stages. Stage 1 focused on the effects of FR treatments on mechanical properties of the treated wood and on identifying the mechanism of thermal degradation. Stage 1 has been described in detail by Winandy et al. (30). Stage 2 focused on the development of a FR-treated plywood serviceability research program (20). This involved a simultaneous progression of studies, each specifically designed to address important voids in our technical knowledge at that time. When evaluating the current and future serviceability of any structural system, such as roof sheathing, two questions need to be addressed. First, what is the current level of performance of the system? Second, if the system currently meets some acceptable level of performance, what is the expected remaining service life? The service life model developed under this FR-treated plywood serviceability program addressed these two concerns. The first objective of Stage 2 dealt with defining chemical mechanisms, exploring the influences of processing factors and service conditions, and assessing the current condition of FR-treated wood in service. The second objective focused on the environmental and exposure conditions imposed on FR-treated wood in service as a result of design and location and making projections of degrade potential with which to predict residual service life. The remaining work of the Stage 2 research program is to finalize development of a reliable tool for predicting residual service life of FR-treated roof sheathing.

MECHANISMS OF THERMAL DEGRADATION

Researchers have long recognized that FR treatments reduce initial strength properties (3-5,7). Post-treatment redrying has been shown to accelerate this initial strength loss (6,31). This initial reduction in strength from FR treatment and redrying was accounted for through modifications to allowable stress design values. What was not foreseen prior to the mid-1980s was that additional in-service reductions in strength might occur when some FR-treated products were exposed to elevated temperatures such as those induced by solar loads on roof systems.

Preliminary investigations had indicated that field problems of FR-treated plywood roof sheathing resulted from

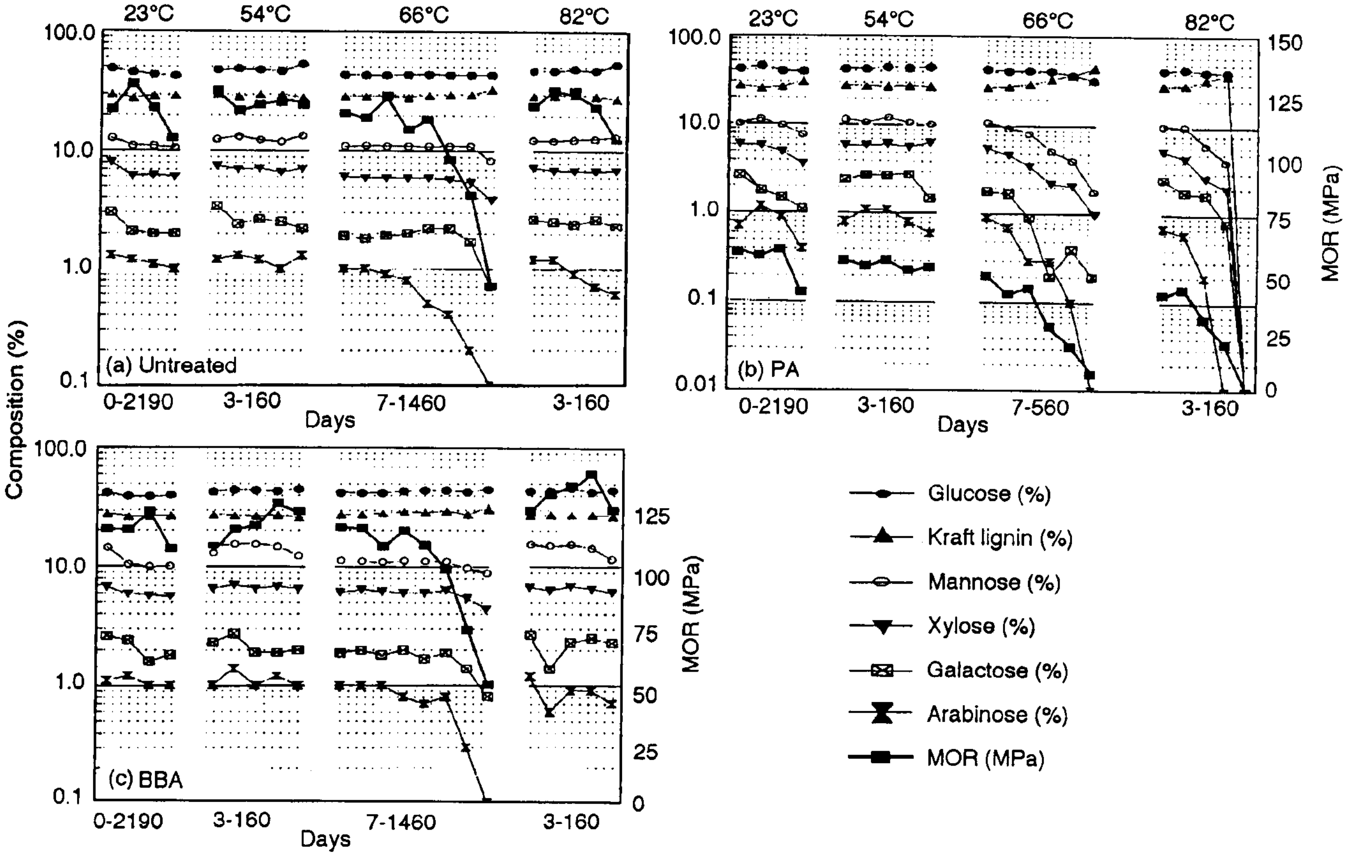

Figure 4.— Relationship between loss in bending strength (MOR) and changes in lignin content and content of individual carbohydrate components of hemicellulose and cellulose for untreated and treated wood (26).

thermal-induced acid degradation of wood carbohydrates by the acidic FR chemicals (12). Subsequent work confirmed the proposed acid-degradation mechanism (8,21,22). This research confirms our initial hypothesis that the relative effects of many FR treatments could be classified by the type of FR chemical employed and the time-temperature combination required to convert the FR formulation into its acidic-functional form (13).

Figures 1 to 3 show the overall effect of extended high-temperature exposure (up to 4 years at 66°C at 75% relative humidity) on bending strength of untreated wood or wood treated with several FR-model formulations; data were compiled from Winandy (21) and Lebow and Winandy (10). These two reports summarized data at 27°, 54°, 66°, and 82°C for up to 4 years. They clearly showed that the thermal effects on strength at any temperature within that range were additive and could be predicted using a cumulative damage model based on performance at any other temperature within that range.

Two FR-model formulations (phosphoric acid (PA) and monoammonium phosphate (MAP)) caused a significant reduction in the initial bending strength of the treated wood as well as a relatively consistent reduction in bending strength relative to time of exposure at high temperature. Untreated wood and wood treated with borax/boric acid (BBA) exhibited little to no reduction in initial bending strength, then seemed to experience a finite period (≤ 60 days) of resistance to thermal degrade. Comparison of other FR treatments, for example, guanylurea phosphate/boric acid (GUP/B), dicyandiamide-phosphoric acid-formaldehyde (DPF), and organophosphonate ester (OPE) showed that the treated wood experienced a measurable initial strength loss and may have experienced a brief period (< 7 days) of resistance to thermal degrade. Thereafter, for each FR-model compound, treated wood experienced a relatively consistent reduction in bending strength over time of exposure at high temperature (Fig. 1). Initially, modulus of elasticity (MOE) was relatively less affected than bending strength, but eventually the effects of treatment and temperature were just as apparent (Fig. 2).

By contrast, the effect of treatment on work to maximum load (WML) was initially more noticeable than the effects on bending strength and MOE (Fig. 3). Since WML is a measure of energy to failure, it is a good indicator of embrittlement. Users have long recognized that many wood treatments result in a less ductile product. Some acid systems lead to a product that is brasher in its failure mechanism. Judging by the significant loss in WML for untreated and all treated wood products at 66°C it is obvious that given a long enough duration of exposure to elevated temperatures, all wood products, treated or untreated, will eventually undergo critical levels of degrade.

The mechanism of strength loss from FR-treatment and from high-temperature exposure was recently shown to be related to changes in the chemical composition of wood. Models for predicting strength loss from changes in wood chemical composition have been developed by Winandy and Lebow (26). These models are based on the strong relationship between loss in strength and loss in hemicelluloses (Fig. 4). Monitoring the degradation of the least-protected side-chain carbohydrate moieties, such as arabinose, provided the most sensitive predictor of early strength loss. The carbohydrates were followed in sensitivity by galactose, mannose, xylose, and glucose.

Previous work had found that the rate of strength degradation for untreated and FR-treated plywood increased as relative humidity increased; a test method was developed to evaluate commercial FR treatments (32). Subsequently, three consensus U.S. standards evolved from that test method (1). To evaluate the data derived from the test method, several kinetics-based models for thermal degradation of FR-treated material were developed (16,31,33). Winandy and Lebow (27) and Lebow and Winandy (8) built on that work to develop a single-stage kinetics-based model to predict the magnitude of thermal degradation for a series of FR-model treatments. They further demon: strated that their single-stage model could accurately predict strength loss across a wide range of temperatures and exposure conditions. Other work has found that strength loss from cyclic thermal exposure was generally similar to that from steady-state temperature exposure when compared on a cumulative time-at-temperature basis (14).

The following critical needs were identified before we could develop the procedure(s) to assess current conditions and to eventually develop a predictive residual service life model for FR-treated plywood roof sheathing. We needed to 1) know the influence of processing effects; 2) develop methods to assess current conditions; 3) know thermal loads; and 4) develop an understanding of critical serviceability/durability factors. Three of these FPL projects, two of which included extramural cooperative agreements, are now complete. The final residual service life modeling program is nearing completion. To the extent possible, the various research components of this program were performed concurrently. Each project is briefly described in the following text.

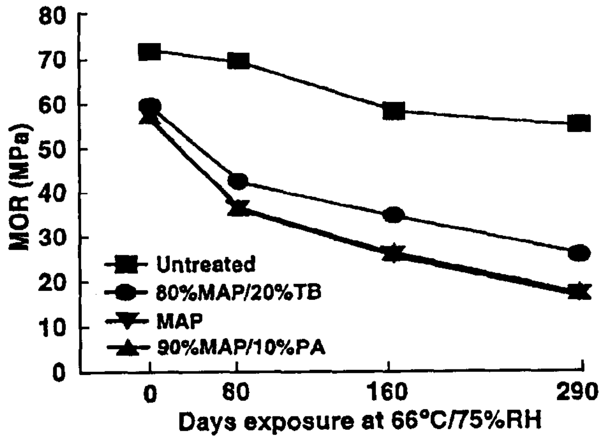

Figure 5. — Effects of FR treatment mixtures on bending strength of 12-mm-thick plywood subsequently exposed to extended exposure at 66°C (22).

PROCESSING FACTORS

The goals of this project were to 1) determine the governing relationships of treatment processing factors, mixtures of chemical components, and post-treatment temperature and moisture factors to in-service performance and to relate these relationships to in-service thermal-induced strength degradation rates; and 2) define the effects of initial plywood quality and its possible interaction with in-service thermal degradation.

Preliminary FPL results indicated that the level of degradation in -mechanical properties and wood composition induced by steady-state laboratory exposure was often less than the magnitude of the degradation experienced in the field (30). These differences in property degradation rates appeared to be related to the severity of the processing factors employed in commercial treating and drying (20). We initially suspected that these factors included the influence of the mixture of various FR chemical components used in a commercial FR formulation, the temperatures employed in kiln-drying FR-treated material after treatment, and the presence or absence of post-treatment drying and/or wetting during storage or construction (13). Some experts also believe that roof-cavity ventilation is a significant factor and research continues to assess its importance. Overall, we found that many product-manufacturing and treatment-processing factors contribute to the differential performance of laboratory and field materials.

Early in this “processing factors” phase of research, key experimental factors were identified using dynamic mechanical analysis of small plywood veneers about 1 mm thick (11). The key factors that influenced thermal degradation were FR retention and in-service moisture content (MC). The results of that study were used in the larger second phase of this project to define experimental factors using full-size, 19-mm-thick plywood specimens (22). Recall that in **Figures 1** to **3,** the length of the period of resistance to thermal degrade was directly related to the initial effect of the FR treatment on strength and appeared to be related to the pH of the treating solution or wood. In the second phase, we proved that control of the treating solution pH by the use of pH buffers, such as borates, could mitigate the initial effect of the FR on strength and then enhance resistance to subsequent thermal degradation (Fig. 5) (22).

We also found that variation in redrying temperatures from 49° to 88°C had little differential effect on the subsequent rate of thermal degradation when the treated plywood was exposed at 65°C for up to 290 days **(Fig. 6).** Further, we showed that the effects of thermal exposure during both redrying and in-service solar loading were cumulative on a time-at-temperature basis (22). Finally, in other work we found that remedial borate treatments were useful in preventing additional thermal degrade (28).

To address our second goal, we studied the influence of plywood quality on thermal degrade of various grades of FR-treated plywood. At the time, the ex-

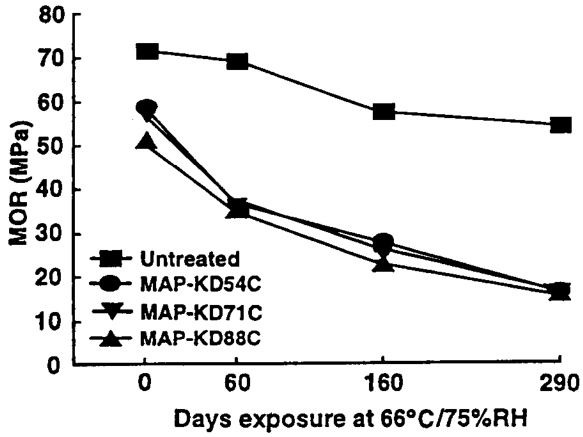

Figure 6. — Effects of redrying temperatures at 54°, 71°, or 88°C on bending strength of 12-mm-thick FR-treated plywood subsequently exposed to extended exposure at 66°C (22).

isting data on thermal effects on FR-treated plywood related to only one very high level of plywood quality. To limit property variability, the early data were obtained from tests of high-quality plywood, which was specially made from nearly clear veneers with no knots or interior voids and only minimal surface imperfections (32). Additional information was then needed to adapt the thermal-effects data in the database to field applications using commercial quality plywood. Lebow and Winandy (9) evaluated four grades and two thicknesses of commercial plywood. The results showed that the rate of strength loss in plywood resulting from FR treatment, post-treatment redrying, and subsequent high-temperature exposure was to a great extent independent of plywood quality or grade. Further, although the various grades of plywood had large absolute differences in strength, these differences remained relatively constant after treatment and exposure. With respect to the influence of plywood thickness, although the initial treatment effect differed for the two plywood thicknesses tested, the relative loss in strength caused by thermal degrade resulting from exposure at high temperatures was similar for both thickness levels. Thus, it now appears that the thermal degrade results of an earlier study (32) using high-quality N-grade plywood are readily applicable to commercial grades and thicknesses.

CONDITION ASSESSMENT

Before we could predict future strength loss for a piece of plywood, we needed information on its current condition. We needed to develop and determine the key nondestructive evaluation (NDE) techniques and appropriate parameters for predicting current strength. We also needed to determine how these parameters should be measured and how to empirically define the relationship between the NDE property and strength.

Considerable concern existed about the in-place strength of FR-treated plywood. In addition, building officials and inspection professionals were frustrated by the lack of NDE tools available for assessing the residual strength of these materials. Definitive relationships between nondestructively measured properties and engineering design properties were needed before NDE techniques could be completely useful.

There are two broad types of NDE methods: chemical and mechanical. Chemical-based NDE utilizes the relationship between changes in wood strength from thermal degradation and changes in wood pH, carbohydrate structure, or wood chemistry (10,18,26). This technique is rapidly becoming better understood and more reliable. LeVan et al. (13) clearly showed that early strength loss during the thermal degrade process was related to changes in hemicellulose composition rather than cellulose or lignin. Sweet and Winandy (18) found that degradation of hemicelluloses was more strongly related to incipient strength loss than was the degree of polymerization of cellulose. They proposed a qualitative model in which early strength loss was initially a function of degradation in hemicellulosic side-chain components like arabinan and galactan (Fig. 4). Next, strength loss involved dissolution of main-chain hemicellulosic components, like xylans and glucomannans, and finally, degradation of cellulose and lignin. These authors proposed that additional work might find this relationship quantitative (18). Current work at FPL is evaluating such models. Quantitative models have been developed to predict residual strength from changes in chemical composition (26). However, chemical tests are often prohibitively expensive because of equipment needs, operator time, and lag time between field inspection and sample collection and test results.

Mechanical NDE often involves proofloading-type tests and the use of concomitant relationships such as the relations between stress wave speed and MOE or stress wave attenuation and strength. The use of these types of mechanical NDE in the field is often complicated by cumbersome equipment. Another problem is inappropriate boundary conditions that limit application by complicating signal processing.

Another variant of mechanical tests is the probe (screw) withdrawal relationship to strength. Screw withdrawal tests were initially conceived by Ross et al. (17). These tests have been found to be simple and reliable indicators of degradation. Winandy et al. (29) defined constitutive relationships between nondestructively measured properties and the bending strength of FR-treated plywood (Fig. 7). These constitutive relationships between screw withdrawal force and residual bending strength were then used in a similar manner as MOE is used to predict bending strength in machine-stress-rated lumber grading. The final step to implementation will be for researchers and the engineering communities to work together to develop consensus precision estimates to enable third-party interpretation of these constitutive relationships.

SERVICEABILITY FACTORS AND THERMAL LOADS

Two goals were established in this part of our research program: 1) define relationships between field and laboratory exposures; and 2) verify and reline the FPL temperature history model for roofs.

In the first project on correlation between laboratory- and field-exposed strength loss, initial FPL results indicated that thermal-induced acid dehydration of wood carbohydrates caused thermal-induced in-service degradation of FR-treated roof sheathing. However, the level of degradation in mechanical properties and wood composition induced by steady-state high-temperature laboratory exposures was correlated to, but less than, the magnitude of the degradation sometimes experienced in the field. Thus, differences between field- and laboratory-induced property degradation rates had to be established for similarly processed FR-treated materials to extrapolate laboratory results to field serviceability.

In 1991, test chambers were initially built for both laboratory and outdoor field exposure in Madison, Wis. (latitude = 43.4°N.). These five field chambers, each holding 96 specimens, have been in use for more than 8 years. The results of the first 3 years of the roof temperature data collection have been reported (25). Roof system temperature histories were reported for interior attic air, exterior air, inner and outer veneers of plywood sheathing, and internal rafter temperatures for both black- and white-roofed structures. Temperatures were measured using thermocouples and have been recorded since October 1991 using a datalogger/multiplexer device.

The maximum temperatures recorded in our 3-year study for black-shingled roofs were 76°, 58°, and 54°C for the top-ply veneer, bottom ply, and internal rafter temperatures, respectively. The maximum temperatures recorded for the white-shingled roofs were 64°, 53°, and 49°C for the top-ply veneer, bottom ply, and internal rafter temperatures, respectively. However, these were 3-year maximums and daily maximums were generally 10° to 20°C lower during the summer and 25° to 45°C lower during the winter. Overall, the plywood roof sheathing of black-shingled roofs was exposed to temperatures above 50°C five times more than the sheathing of white-shingled roof systems (364 hr./yr. for black shingles vs. 73 hr./yr. for white). On sunny days, the temperature of the top ply of plywood roof sheathing under black shingles was generally 5° to 8°C warmer than that of identical white-shingled roof structures. However, after dark, the black-shingled roof temperature quickly cooled and temperatures were similar to those of white-shingled roofs.

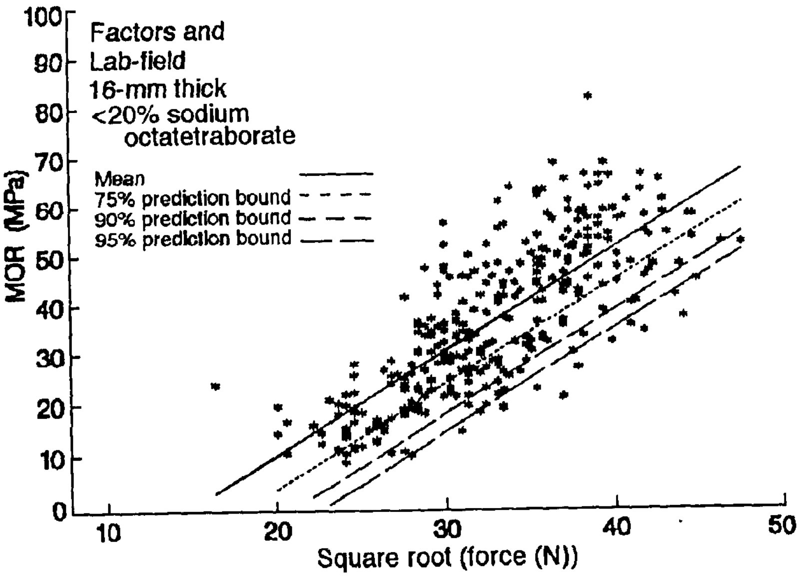

Figure 7. — Mean and lower bounds for predicting bending strength from screw-extraction force measurements on 16-mm-thick, phosphate-treated plywood with ≤ 20 percent borate (28).

These data confirmed that the roof sheathing plywood and roof truss lumber temperatures, which are the primary factors influencing thermal degrade of FR-treated materials, are primarily controlled by solar gain. However, the effect of MC was not evaluated, nor was MC controlled by attic ventilation.

Five additional field chambers were constructed in 1994 under a USDA Competitive Grant and an extramural cooperative project with the Mississippi Forest Products Laboratory near Starkville, Miss. These new chambers provided for direct comparisons between northern and southern U.S. climates as well as comparisons between dry and humidified attics. Roof temperature data are now available for 8 years in Madison, Wis. (latitude 43.4° N.) and 4 years in Starkville, Miss. (latitude 33.5° N.) (24).

The maximum temperatures recorded in the 4-year Mississippi study for black-shingled roofs in dry unvented buildings were 78°, 63°, and 58°C for the top-ply veneer, bottom ply, and nominal 2 by 8 (38- by 184-mm) rafters (internal temperatures), respectively. The maximum temperatures recorded for the matched dry unvented Wisconsin roof systems over an 8-year period were 75°, 59°, and 54°C respectively.

The maximum temperatures recorded in the 4-year Mississippi study for black-shingled roofs in heavily humidified buildings were the coolest at 74°, 58°, and 54°C for the top-ply veneer, bottom ply, and 2 by 8 rafters (internal temperatures), respectively. Daily maximums and annualized temperature data for each wood component exhibited similar differences to that of the previously reported 3-year Madison data (25). These results clearly indicated that the temperatures of wood components used in wood roof systems were dictated more by the influx of radiant solar energy than by ambient outside air temperatures (24).

In both Wisconsin and Mississippi, matched small plywood specimens were exposed in steady-state laboratory exposure chambers (65°C) and diurnal field exposure chambers. Mechanical testing of these specimens has recently been completed and analysis is now underway (24). This analysis will provide a basis for the development of precision estimates between laboratory strength-temperature effects and field (real world) strength-temperature effects. The eventual goal is to develop an empirical comparative relationship based on the correlation between matched laboratory and field data. This relationship will be

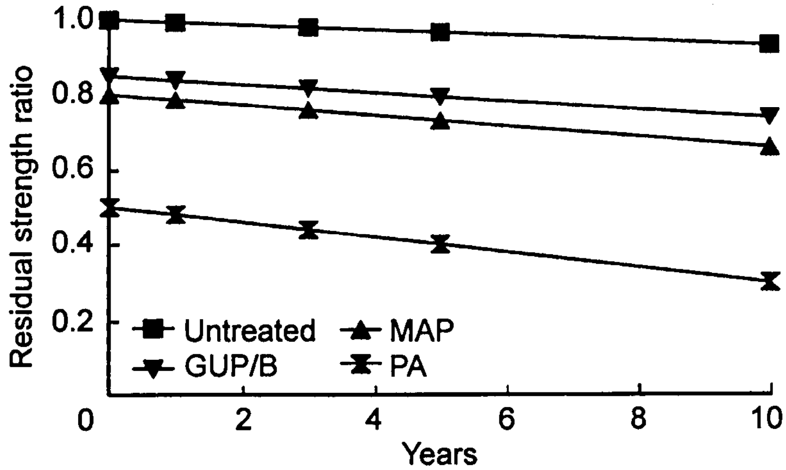

Figure 8. — Predicted change in residual strength ratio, defined as ratio of strength of treated to untreated wood, over a simulated 10-year exposure (25) in north central United States using kinetics-based models (8).

further modified based on historical weather data from other locations to predict field performance in those locations based on the model being developed in the second phase of this project on serviceability factors and thermal loads.

The goal of the second phase of research on serviceability factors and thermal loads was to develop and verify the FPL Roof Temperature Model. In this phase, an empirical model to predict roof temperatures and MCs in plywood roof sheathing based on historical weather data from any location was developed (19). The FPL Roof Temperature Model has been adapted for FR-treated plywood and verified with moisture and temperature data, which were collected under an extramural cooperative project with the University of Illinois. The annual roof-temperature profiles used in ASTM Standard D 6305 (1) for various localities across the United States were generated using this model. In the serviceability models discussed in the following section of this paper, the FPL Roof Temperature Model provides the basis for adapting in-service temperature and climate factors from locations with known conditions to other untested locations.

PREDICTING RESIDUAL SERVICEABILITY

The goal of this final project was to develop the best service life model to evaluate the residual service life of FR-treated roof sheathing plywood. Predicting the residual service life of this sheathing requires a service life model that incorporates information from many of the previously outlined studies and also provides a fundamental framework for adding site- and exposure-condition factors. The model generates a condition assessment (see Condition Assessment section) by using a nondestructive assessment of residual strength based on a screw withdrawal test. This condition assessment is then adjusted to reflect predicted material degradation rates derived from kinetic thermal degradation models (see Mechanisms of Thermal Degradation section) and adjusted for predicted field exposure using structure-specific thermal performance models (see Serviceability Factors section) to estimate the remaining service life of FR-treated plywood roof sheathing. Such a model is now being studied comprehensively and further developed. A first attempt at such a residual serviceability model has been reported (23). The predicted strength losses and field serviceability from these kinetic degrade models paralleled actual field performance **(Fig. 8).**

Untreated wood lost 4 percent strength when our predictive models (8) were used to simulate a 10-year exposure in Madison, Wis. (25). The preliminary results indicated that wood treated with the worst FR-model treatment (phosphoric acid) could be expected to experience an additional 20 percent loss in original in-service strength after the 10-year simulation. Wood treated with other FR-model chemicals, such as 56 kg/m^3 of MAP or a 70/30 percent mixture of GUP/B, would experience intermediate levels of strength loss. Based on time-temperature superposition, the loss in capacity in warmer, sunnier climates would be somewhat greater. Some portions of this information are currently being introduced into US. design codes and standards. An extensive research project is currently underway at FPL to develop more robust serviceability models. When finalized, these serviceability models will aid code officials, regulators, contractors, and engineers in determining replacement time schedules for any FR-treated plywood undergoing acid-catalyzed thermal degradation.

SUMMARY

Research programs at the FPL are focusing on technologies aimed at extending the service life of wood used as structural systems by providing a more accurate condition assessment for residual serviceability analysis. Programs such as these will eventually increase the utility and durability of wood-based structures, increase the reliability and long-term efficiency of such structures, and decrease environmental impacts by making existing products last longer, thereby decreasing the need for replacement products. The ongoing research programs described in this paper focus on predicting the effects of FR treatments on wood properties. The FR Serviceability Model takes a multidisciplinary approach to predict the residual service life of thermally degraded FR-treated plywood. First, it assesses the current residual condition or strength of FR-treated material. Then it predicts future thermal loading based on past temperature history for material in that use and in that locality. Finally, it estimates the rate of future degradation of the material properties based on kinetic models using those predicted elevated temperature exposures.

LITERATURE CITED

1. American Society for Testing and Materials. 1998. Annual Book of Standards. Vol. 4.10; Standard test method for evaluating the flexural properties of tire-retardant treated softwood plywood exposed to elevated temperatures, ASTM D 5516-94; Standard test method for evaluating the effects of fire-retardant treatments and elevated temperatures on strength properties of fire-retardant treated lumber, ASTM D 5664-95; Standard practice for deriving allowable stress design adjustments for fire-retardant treated softwood plywood, ASTM D 6305-98. ASTM, West Conshohocken, Pa.

2. American Wood-Preservers' Association. 1998. Annual Book of Standards. Fire retardant formulations, P17-98; Structural lumber-fire retardant treatment by pressure processes, C20-98; Plywood-fire retardant treatment by pressure processes, C27-98. AWPA, Granbury, Tex.
3. Gerhards, C.C. 1970. Effect of fire-retardant treatment on bending strength of wood. Res. Pap. FPL-RP-145. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
4. Graham, R.D. 1964. Strength of small Douglas-fir beams treated with tire retardants. *In:* Proc. of American Wood Preservers' Assoc. 60:172-177. AWPA, Granbury, Tex.
5. Jessome, A.P. 1962. Strength properties of wood treated with fire retardants. Rept. 193. Forest Prod. Res. Branch, Dept. of Forestry, Ottawa, Ontario, Canada.
6. Johnson, J.W. 1967. Bending strength of small joists of Douglas-fir treated with fire retardants. Rept. T-23. Oregon State Univ., Forest Res. Lab., Corvallis, Oreg.
7. King, E.G., Jr. and D.A. Matteson, Jr. 1961. Effects of fire-retardant treatments on the mechanical properties of Douglas-fir plywood. Lab. Rept. 90. Douglas-fir Plywood Assoc., Tacoma, Wash. 14 pp.
8. Lebow, P.K. and J.E. Winandy. 1999. Verification of kinetics-based model for long-term effects of fire-retardants on bending strength at elevated temperatures. Wood and Fiber Sci. 31(1):49-61.
9. Lebow, S.T. and J.E. Winandy. 1998. The role of grade and thickness in the degradation of fire-retardant-treated plywood. Forest Prod. J. 48(6):88-94.
10. __________ and __________, 1999. Effect of tire-retardant treatments on plywood pH and the relationship of pH to strength properties. Wood Sci. and Technology 33(4): 285-298.
11. Le Van, S.L. 1993. Parametric evaluation of dynamic mechanical analysis of variables influencing strength degradation. M.S. thesis. Dept. of Chemical Engineering, Univ. of Wisconsin, Madison, Wis.
12. __________ and J.E. Winandy. 1990. Effects of fire retardant treatments on wood strength: A review. Wood and Fiber Sci. 22(1):113-131.
13. __________, R.J. Ross, and J.E. Winandy. 1990. Effects of fire retardant chemicals on the bending properties of wood at elevated temperatures. Res. Pap. FPL-RP-498. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
14. __________, J.M. Kim, R.J. Nagel, and J.W. Evans. 1996. Mechanical properties of fire-retardant-treated plywood after cyclic temperature exposure. Forest Prod. J. 46(5): 64-71.
15. National Association of Home Builders. 1990. Home builders guide to tire retardant treated plywood: Evaluation, testing and replacement. NAHB, National Res. Lab., Washington, DC. 65 pp.
16. Pasek, E.A. and C.R. McIntyre. 1990. Heat effects on fire retardant-treated wood. J. of Fire Sciences 8:405-415.
17. Ross, R.J., J.L. Cooper, and Z. Wang. 1992. In-place evaluation of fire-retardant-treated plywood. *In:* Proc. of the 9th Non-destructive Evaluation Conf. September 1991. Washington State Univ.. Pullman. Wash. pp. 247-252.
18. Sweet, MS. and J.E. Winandy. 1999. Influence of degree of polymerization of cellulose and hemicellulose on strength loss in fire-retardant-treated southern pine. Holzforschung 53(3):311-317.
19. TenWolde, A. 1997. FPL roof temperature and moisture model. Res. Pap. FPL-RP-561. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
20. Winandy, J.E. 1994. Serviceability modeling of fire-retardant-treated plywood roof sheathing. *In:* Proc. of Pacific Timber Engineering Conf. Vol. 2. Gold Coast, Queensland, Australia. July 11-15, 1994. Timber Research and Development Council, Fortitude Valley, Queensland, Australia. pp. 292-297.
21. __________, 1995. Effects of tire retardant treatments after 18 months of exposure at 150°F (66°C). Res. Note FPL-RN-0264. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
22. __________, 1997. Effects of fire retardant retention, borate buffers, and redrying temperature after treatment on thermal-induced degradation. Forest Prod. J. 47(6):79-86.
23. __________, 1998. Using kinetics-based models to address serviceability concerns for fire-retardant-treated wood at elevated in-service temperatures. *In:* Proc. of 5th World Conf. on Timber Engineering. August 16-21, 1998. Montreux, Switzerland. Swiss Federal Inst. of Technology. Lausanne, Switzerland.
24. __________, H.M. Barnes, and C. Hatfield. 2000. Roof temperature histories in matched attics in Mississippi and Wisconsin. Res. Pap. FPL-RP-589. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
25. __________ and R. Beaumont. 1995. Roof temperatures in simulated attics. Res. Pap. FPL-RP-543. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
26. __________ and P.K. Lebow. 2001. Modeling wood strength by chemical composition. Part I. An individual component model for southern pine. Wood and Fiber Sci. 33(1).
27. __________ and __________, 1996. Kinetic model of the effects of fire retardants on properties of wood at elevated temperatures. Wood and Fiber Sci. 28(1):39-52.
28. __________ and E.L. Schmidt. 1995. Preliminary development of remedial treatments for thermally degraded fire-retardant-treated wood. Forest Prod. J. 45(2):51-52.
29. __________, P.K. Lebow, and W. Nelson. 1998. Development of models to predict bending strength from a test of screw-withdrawal force for FRT plywood roof sheathing. Res. Pap. FPL-RP-568. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
30. __________, S.L. LeVan, and R.J. Ross. 1991. Fire-retardant-treated wood: Research at the Forest Products Laboratory. *In:* Proc. of the 2nd Inter. Timber Engineering Conf. Vol. 4. pp. 69-74. TRADA, London, U.K.
31. ____________________, E.L. Schaffer, and P.W. Lee. 1988. Effects of fire retardant treatment and redrying on the mechanical properties of Douglas-fir and aspen plywood. Res. Pap. FPL-RP-485. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
32. ____________________, R.J. Ross, S.P. Hoffman, and CR. McIntyre. 1991. Thermal degradation of fire-retardant treated plywood: Development and evaluation of a test protocol. Res. Pap. FPL-RP-501. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
33. Woo, J.K. 1981. Effect of thermal exposure on strength of wood treated with fire retardants. Ph.D. thesis. Univ. of California, Berkeley, Calif. 112 pp.