Mechanical Property Loss and the Occurrence of Wood Decay During Experimental Outdoor Aging of Wood-Based Panels

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Abstract

Small specimens of sheathing-grade oriented strandboard (OSB) and sheathing-grade plywood were evaluated for retention of mechanical properties in exterior exposure over a series of exposure times. In contrast to previous studies of this nature, specimens at prolonged exposure times were also evaluated (in something more than a cursory manner) for presence of decay. Specimen size and mounting configuration had been selected to maximize wetting- and drying-induced stress on adhesive bonds but discourage water retention and thus the likelihood of decay. Mechanical properties decreased progressively with exposure time, at a decreasing marginal rate, without a steady level ever being attained. All panel types included in this study became infested with decay fungi by 7 years of exposure, although infestation was clearly most severe in panels fabricated from aspen, and decay-induced degradation evidently became more pronounced with progressive exposure time beyond 7 years. In this study, the assumption that test fence exposures can be designed to induce moisture-cycling-induced stresses on adhesive bonds while simultaneously excluding infestation by decay fungi proved to be erroneous. Infestation was apparently by decay fungi adapted to rapid fluctuations in moisture and temperature conditions, species that are not recognized as commonly causing decay of wood products.

Introduction

This paper reports on the last phase of the most recent of a series of studies concerning durability evaluation of structural flakeboards. The series of studies was originated by adhesives scientists at the USDA Forest Service, Forest Products Laboratory; previous publications were Baker and Gillespie (1978), River et al. (1981), River (1994), and Okkonen and River (1996). The first in the series of studies was undertaken in support of a U.S. Forest Service (USFS) research program, initiated in 1972, that concerned production of structural flakeboards from forest residues.

Historical Background

At the inception of the USFS structural flakeboard program, a structural flakeboard industry did not yet exist in the United States. The then-current product standard for wood particleboard, U.S. Commercial Standard CS236-66 (U.S. Dept. of Commerce 1966), was the only product standard in the United States that was remotely applicable to structural flakeboard. Standard CS236-66 outlined 10 basic particleboard grades in two types ("interior" and "exterior"). The "exterior type" particleboards addressed in CS236-66 found commercial use as structural sub-flooring, primarily in manufactured housing (Jorgensen 1978), and as overlaid siding. The product standard did not distinguish between true exterior applications and applications less stringent than exterior but in which greater bond durability than could be attained with urea-formaldehyde adhesives was deemed necessary.[1] Baker and Gillespie (1978) followed the precedent set by CS236-66, as evidently did Geimer et al. (1973), McNatt (1978), and Wilson (1984). A paradigm has since become established in panel production and residential building industries (APA 1994) that the overwhelming majority of structural flakeboard panels are produced for and used in "Exposure 1" applications, where the product is not exposed indefinitely to the weather. In Exposure 1 applications, concern with bond durability relates to weather exposure that may occur during construction.[2] If an Exposure 1 application is assumed, determination of panel behavior in exterior exposure tests is useful when exposure periods are similar to what might be experienced during construction delays. Determination of panel behavior in exterior exposure for periods longer than this would logically be of limited utility, although good performance in such extended exposure testing could indicate product robustness. Additionally, knowledge about the performance of products employed outside their intended exposure can be valuable in contexts such as forensic engineering or building inspection, where either analysis of failure or estimation of residual mechanical properties could prove useful.

Findings of Published Long-Term Exterior Exposure Studies

Long-term[3] exterior exposure has been used to demonstrate long-term durability of phenolic adhesive bonding in plywood (Gillespie and River 1976) and in small specimens of adhesive-bonded lumber (Caster 1980), with bond durability characterized by measured strength and percentage wood failure in glueline shear. Long-term exterior exposure studies have also been used in an attempt to characterize long-term bond durability in wood composition materials (Jokerst 1968; Geimer et al. 1973; Beech et al. 1974; Dinwoodie 1981; Alexopoulos 1992; River 1994; Sekino and Suzuki 2002), with bond durability characterized by relative lack of thickness swelling of the product or by retention of one or more mechanical properties (such as internal bond strength, bending strength, stiffness). All these studies included panels that either were not necessarily intended, or explicitly were not intended, for exterior exposure. Some of these studies distinguished between adhesive bonding systems (Jokerst 1968; Beech et al. 1974; Dinwoodie 1981). Other studies distinguished between adhesive content levels (Geimer et al. 1973) or between a variety of commercial panels incorporating a variety of adhesive types and content levels (Sekino and Suzuki 2002). Alexopoulos (1992) and River (1994) limited their investigations to panels bonded with exterior adhesives but in which some panels (River 1994) or all panels (Alexopoulos 1992) were for Exposure 1 rather than exterior use applications. River

[1] The American National Standard for Mat-Formed Particleboard (ANSI 208.1), which succeeded CS236-66 followed the precedent set by CS236-66 and did not promulgate a range of different bond durability classifications for panels bonded with "exterior" adhesive. The first product standard to make such a distinction was PS-1-74. The Performance Standards for Structural-Use Panels (PRP-108 and PS-2) that were developed during the 1980s recognized different bond durability levels for panels with different levels of anticipated exposure to wetting over their lifetimes.

[2] Panels marketed for "Exposure 1" applications do not necessarily have equivalent bond durability. Wu and Suchsland (1997) found considerable variation in thickness swelling of different oriented strandboards, all of which were marketed for use in Exposure 1 applications, with board intended for web material of I-joists showing substantially less swelling than board marketed as wall or roof sheathing. In addition, some proprietary strandboard products, marketed for Exposure 1 applications, have superior bond durability relative to commodity-grade strandboard sheathing or single-layer flooring (Groom 2005).

[3]For this discussion, "long-term" means periods in excess of 3 years, and thus considerably beyond what could reasonably be expected as a result of construction delays

(1994) identified correlations between behavior in laboratory accelerated-aging test procedures and behavior at various exterior exposure periods. Most of the studies characterized time trends in degradation of panel properties, the most recent work (Sekino and Suzuki 2002) characterizing time trends in mathematical terms. According to Sekino and Suzuki (2002), the bending properties of mat-formed panels tend to decrease linearly with the logarithm of exposure time, or stated in more general terms, the bending properties progressively degrade with exposure time at a decreasing marginal rate. Stated in this general way, the time trend reported by Sekino and Suzuki (2002) concurs with the findings of River (1994), Geimer et al. (1973), and Alexopoulos (1992), although with imperfect consistency. It also concurs with what O'Halloran and Erb (1981) stated was the most commonly observed time trend in the research literature. In contrast to the time trends for bending properties, those for degradation of internal bond strength tend to be inconsistent between studies (Jokerst 1968; Beech et al. 1974; Dinwoodie 1981) and sometimes within a study (River 1994).

In the studies discussed in the preceding paragraph, specimens were, without exception, small and configured with minimal or no lap contact with mounting supports, and usually lacked any coating[4] (which might fail during the exposure period). The combination of specimen size, treatment, and exposure was devised to limit specimen water retention after rain wetting, thereby inhibiting growth of decay fungi. Only in the most recent of these studies (River 1994; Sekino and Suzuki 2002) was any presence of decay reported. River (1994) observed decay in the sapwood of solid southern yellow pine (SYP) specimens that were included in the study as benchmark material; he made no mention of observed decay in any of the adhered wood panel materials.[5] Sekino and Suzuki (2002) observed decay in oriented strandboard (OSB) at 5 or more years of exposure and in melamine-urea-bonded medium-density fiberboard (MDF) at 8 or more years of exposure. The presence of decay in OSB or MDF was not readily apparent in the mechanical property data of these materials (Sekino and Suzuki 2002), whereas the presence of decay in SYP sapwood was readily apparent in the material's internal bond data (River 1994). The observations of River (1994) and Sekino and Suzuki (2002) suggest that despite reasonable attempts to limit rainwater retention in the specimens employed in prolonged exterior exposure tests, the conventional assumption that specimens remain free of significant wood decay is not necessarily justified. Their observations also indicate that, contrary to what occurs with solid wood, decay propagation during test fence exposure may not necessarily make itself evident in the mechanical property data for wood composition materials.

This paper concerns the final stage of a study (Okkonen and River 1996) that followed a course similar to that of an earlier study (River 1994). This study, in contrast to the previous one, included only commercial panels rated for Exposure 1 applications. Okkonen and River (1996) reported early data from this study, specifically data for laboratory accelerated-aging (AA) tests and for 1 year of exterior exposure. They reported that the data for these Exposure 1 panels fit reasonably well into the correlational database developed previously (River 1994) that included

[4] In these studies, test specimens were 0.3 by 0.3 m or smaller and generally were unpainted. Jokerst (1968) and Geimer et al. (1973) included a small number of painted specimens.
[5] The presence of decay in solid SYP specimens but not in plywood or flakeboard specimens could hypothetically be explained by deep surface checking in the solid wood specimens, which can allow rapid water entry to specimen interiors. Adhered wood products generally are not prone to deep checking. Surface checking in plywood, although common, is generally restricted to the surface veneers and does not extend into cross-band or core layers.

solid wood and a variety of phenolic-bonded adhered wood panels. Addition of the data for Exposure 1 panels into the correlational database had little effect on the prediction equation for bending strength after 1 year exposure that used bending strength after laboratory AA as its independent (predictive) variable. It was evident, however, that the commercial Exposure 1 OSB panels underwent substantially more swelling and greater decline in mechanical properties (in both cyclic AA test procedures and exterior exposure) than did the commercial structural flakeboard panels that were evaluated in the previous study (River 1994).

Study Procedure and Approach

This paper presents the longer term exposure data that Okkonen and River (1996) indicated would be published at a later date. Because the panels were for Exposure 1 applications, and thus not intended for indefinite exterior exposure, the adequacy of laboratory AA test procedures for predicting mechanical properties after long-term exposure is not addressed in this paper. The exposure data are instead evaluated from the perspective of general exposure time trends. A more careful evaluation of the presence of decay than has previously been undertaken in test fence exposure studies is also reported.

The panel materials were as described by Okkonen and River (1996), namely aspen OSB, sheathing-grade Douglas-fir plywood, sheathing-grade SYP plywood, and sheathing-grade aspen plywood, all of which were bonded with phenol-formaldehyde-based adhesives. Panels of standard 1.2- by 2.4-m (4- by 8-ft) dimension were purchased from several lumberyards in or near Madison, Wisconsin. The plywood panels contained veneer defects (knots and veneer splits) permissible in sheathing-grade plywood. As previously described (Okkonen and River 1996), panels were cut into 51- by 305-mm bending specimens, with the 305-mm dimension parallel with the 2.4-m dimension of the panels. There were 40 specimens of each panel type. Plywood specimens randomly contained defects; specimens were not sorted or selected based on defect presence or severity. The plywood specimens, however, were free of veneer overlaps and contained no large veneer gaps. Specimens were conditioned to equilibrium at 22°C and 65% relative humidity, and the thickness and weight of each specimen were measured. Ten randomly selected specimens of each panel type were tested in static bending. The remaining specimens were placed on exterior test fences near Madison, Wisconsin, as reported by Okkonen and River (1996).

The fences were south facing and inclined 30° from vertical. Each end of each specimen was secured to a mounting cross-piece with a round-head brass screw and kept out of contact with the mounting cross-piece with a 6-mm-long plastic grommet. Each grommet had an outside diameter of approximately 8 mm; the mounting screw passed through the grommet's hole. The fence and its specimen-mounting configuration were designed to maximize wetting- and drying-induced stress on adhesive bonds of the specimens but discourage water retention and thus the likelihood of decay establishment.

Five specimens of each panel type were removed from exterior exposure at 1, 2, 7, 8, and 11.5 years. Specimens removed from exposure were reconditioned to equilibrium at 22°C and 65% relative humidity, measured for thickness, and tested in static bending; specimens removed at 11.5 years of exposure were also weighed after conditioning (before being tested in static bending). Bending properties—modulus of rupture (MOR) and modulus of elasticity (MOE)—were calculated based on reconditioned thickness, following the precedent of River (1994) and Okkonen and River (1996).

Note was made of presence of fungal fruiting bodies on specimens removed from exterior exposure for testing at 7 years. Light microscopic diagnosis of the presence of wood decay and/or blue-stain-type hyphae was made in all specimens removed from exposure for testing at 7 and 8 years. Microscopic samples were prepared from interior portions of each specimen, as far from any edge as possible, so as to minimize any effects that edge-proximity might have on colonization. A cursory field observation of presence of fungal fruiting bodies was also made at 8 years plus 6 weeks of exposure, on those specimens that remained on the test fences, and at roughly 6-months intervals thereafter until final removal of specimens from exposure at 11.5 years.

Results

Time trends of reconditioned (irreversible) thickness swelling are shown in Figure 1. In general, all the commercial strandboards underwent progressively greater (irreversible) thickness swelling over the course of exposure. Figure 1 suggests a reduction in thickness in three of the four strandboards between 7 and 8 years of exposure. Group *t*-tests indicated that irreversible thickness swelling values for the strandboards at 7 years were statistically indistinguishable from those at 8 years exposure; alpha levels (probability of greater *t* values) were 0.25, 0.15, and 0.32 for OSB 1, OSB 3, and OSB 4, respectively. Although group *t*-tests failed to detect statistical differences between thickness swelling at 7 and 8 years of exposure, the possibility that measured thickness swelling was slightly less at 8 years of exposure cannot yet be dismissed. Specimens removed from the test fence at 8 years could plausibly have been drier at time of removal than corresponding specimens removed from the fence 1 year earlier. If this were the case, sorption hysteresis could have played a role in moisture content attained during re-

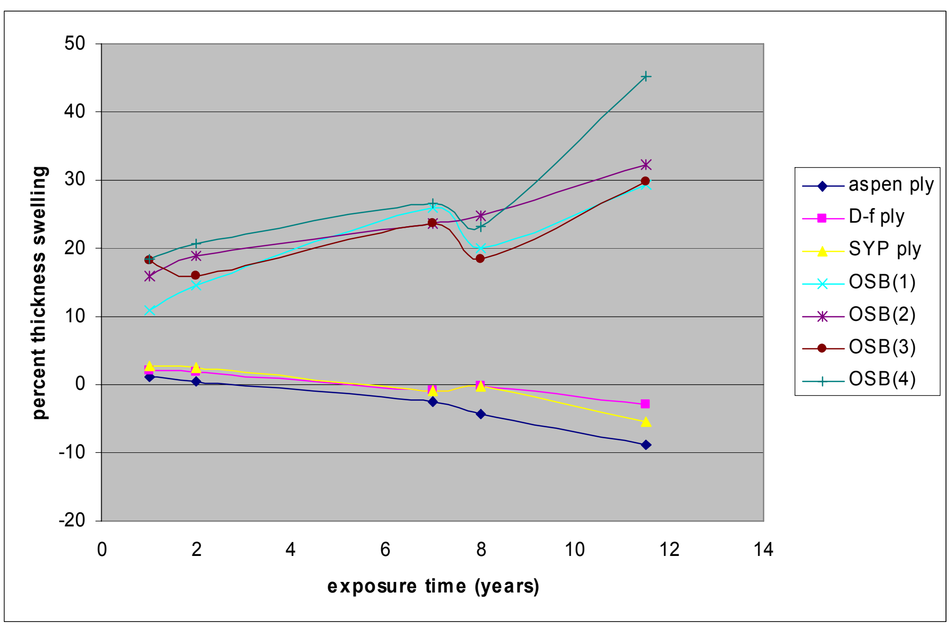

Figure 1: Thickness swelling as a function of exposure period

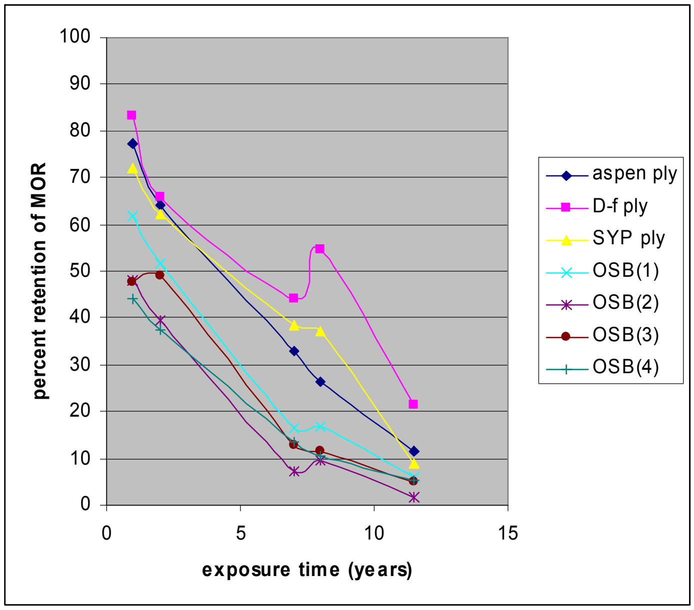

Figure 2: Retention of bending strength as a function of exposure period

conditioning.

Beyond 8 years of exposure, progressive thickness swelling with time in all OSBs again became apparent. The plywood panels showed slight irreversible thickness swelling at 1 and 2 years of exposure[6] but showed thickness losses at 7 years of exposure or beyond. This would be consistent with erosion of veneer surfaces, which in aspen plywood generally was visually perceptible on specimen top surfaces (those facing the sun) by 8 years of exposure. In aspen plywood specimens, the (relatively thin) surface veneer facing the sun was nearly eroded away by 11.5 years of exposure. No obvious delamination in plywood specimens was observed over the course of exposure. The lack of veneer delamination over 11.5 years of exterior exposure contrasts with the experiences of Koch (1970), Black et al. (1976), and Biblis (2000)[7] and indicates that adhesive bonding in all the plywoods in this study was well executed.[8]

Time trends in bending property values are shown in Figures 2 and 3. The most rapid loss in

[6] The irreversible thickness swelling displayed by plywood at 1 and 2 years of exposure is probably due in part to sorption hysteresis. Specimens reconditioned to equilibrium after exterior exposure generally do not attain the same moisture content as they would if conditioned to equilibrium at the same set of conditions from a drier set of conditions. Failure to account for sorption hysteresis can have a noticeable effect on calculated dimensional stability values (Suchsland 1972). Although correct experimental procedures will avoid the confounding influence of sorption hysteresis, the research literature concerning dimensional stability of adhered wood products is dominated by studies in which the phenomenon of sorption hysteresis was erroneously ignored (Carll 1997)

[7] Koch (1970), Black et al. (1976), and Biblis (2000) all investigated plywoods adhered with phenolic adhesives, but the exact adhesive formulations undoubtedly differed. Koch (1970) investigated a variety of adhesive formulations, with regard to phenolic solids contents and the use of different fillers and extenders

[8] Delamination in plywood exposed to cyclic wetting has sometimes been found to be associated with the veneers (Caster 1980), more specifically with enlargement of lathe checks in the veneers (Carroll et al. 1969), where the failures take place partially in gluelines and partially in the veneers. Thus, the lack of obvious delamination in the plywoods indicated not only appropriate choice of adhesive formulation and of gluing techniques, but also well-executed veneer-production techniques.

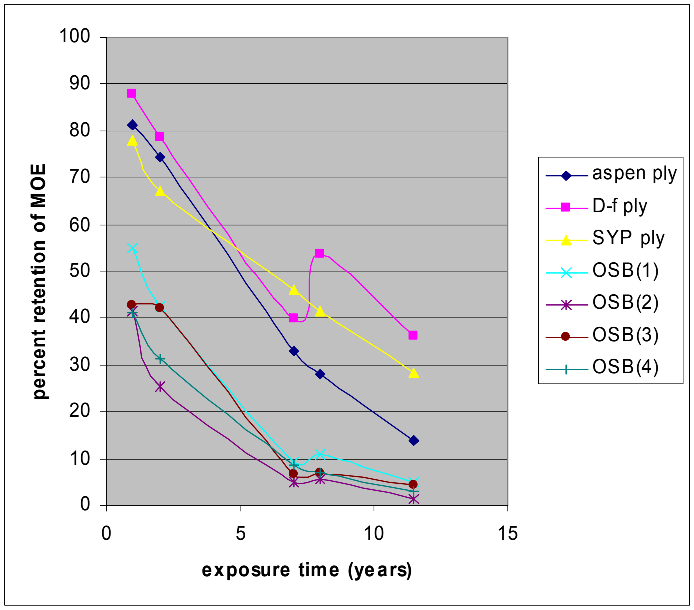

Figure 3: Retention of bending stiffness as a function of exposure period

property values invariably occurred during the first year of exposure. In addition, the rate in loss of property values between 0 and 7 years exposure invariably exceeded that between 7 and 11.5 years of exposure. The trend, generally reported in the research literature, for progressive reduction in mechanical properties at a decreasing marginal rate was, for the most part, observed for all panel types included in this study. It is worth noting that although progressive degradation generally occurred at a decreasing marginal rate, none of the panel types showed any indication that they might eventually reach a plateau condition at which properties would cease to degrade with time. A model for property retention of the form suggested by Sekino and Suzuki (2002) was found to fit the data as well as any model:

$$\text{retention} = A - B[\ln(\text{time})] \qquad (1)$$

where retention is expressed in percentage and time is exposure time in years. Regression coefficient and intercept values for Equation (1) are given in Table 1.

At 7 years of fence exposure, fruiting bodies of wood decay fungi, although small (the largest less than 30 mm in the longest dimension), were evident on more than half the specimens fabricated from aspen (both plywood and OSB). In contrast, no fungal fruiting bodies were observed on any of the softwood plywood (Douglas-fir or Southern Pine). On the aspen plywood, fruiting bodies of white-rot fungi were observed, while on aspen OSB, fruiting bodies of both brown-rot and white-rot fungi were observed.[9] The species identified as present are listed in Table 2; although all are wood decay fungi, none is recognized as commonly causing decay of wood products (K. Nakasone, personal communication). One of the white-rot decay fungi observed, *Peniophora cinerea*, is known to specialize in colonization and decay of twigs and small branches, often while they are still attached to the tree. Twigs and small branches have

[9] In no case were fungal fruiting bodies of two different species observed on the same test specimen.

Table 1: Regression coefficients for Equation (1)

Material	Regression coefficients for MOE retention		Regression coefficients for MOR retention	
	A	*B*	*A*	*B*
Douglas-fir plywood	88.5	19.9	80.4	17.6
SYP plywood	81.4	21.0	76.6	22.8
Aspen plywood	86.0	28.1	80.4	26.4
OSB 1	58.1	22.0	67.4	25.1
OSB 2	39.9	16.7	49.8	20.0
OSB 3	47.4	19.0	53.9	20.2
OSB 4	43.2	17.3	48.6	18.3

Table 2: Species of which fruiting bodies were observed at 7 years exposure

Decay type	Species observed
White-rot	*Hyphoderma praetermissum, Meruliopsis corium, Peniophora cinerea*
Brown-rot	*Dacrymyces minor, Antrodia variiformis*

relatively small wood volume and relatively high surface area and are thus subject to rapid changes in moisture content and temperature, and in this regard are conceptually similar to the test specimens of this study.

Microscopic examination of specimens from 7 and 8 year exposures showed clear evidence of colonization by decay-type fungi and in many cases by stain-type hyphae, as well. Micrographs from specimens of each of the four panel types, removed from fence exposure at 7 years, are shown in Figure 4. Barely perceptible, if any, increases in colonization were observed between 7 and 8 years exposure.

The relative degree of colonization and cellular damage by decay fungi roughly correlated inversely with the relative natural durability of the wood of each species (FPL 1999). For example, the aspen panel products (Figure 4, C and D) showed greater infestation by hyphae of decay fungi than did the Douglas-fir plywood (Figure 4, B) or the SYP plywood (Figure 4, A). As discussed later, average weight losses found during test fence exposure also roughly parallel these differences. The differences also concur with the observations of Laks et al. (2002) in laboratory decay tests of panel products. Colonization by stain-type hyphae (as opposed to decay-type fungi) was roughly as great in SYP plywood as in panels fabricated from aspen.

As indicated previously, field observations were made at approximately 8 years plus 6 weeks of exposure time (late May 1999) on specimens that remained on the test fences. At that time, all the remaining OSB test specimens were extensively covered with fruiting bodies of wood decay fungi, while the plywood specimens (both softwood and aspen) were devoid of fungal fruiting bodies.[10] No fruiting bodies had been observed 6 weeks earlier, when five specimens of each

[10] In May 1999, 70 individual specimens remained on the fence. Of these, 32 were removed in October 2002 for measurement and testing. Thirty-five specimens would have been removed in October 2002, but 3 of those 35

panel type had been removed from the fences at 8 years of exposure. This indicated that in test fence specimens with appreciable decay, fruiting bodies can develop rapidly, just as they do in the wild state on natural substrates. No fungal fruiting bodies were observed at any of the subsequent 6-month inspection intervals.[11] Most of the species listed in Table 2 form small, ephemeral fruiting bodies, prone to removal by environmental conditions. In particular, the brown-rot jelly fungus *Dacrymyces minor* has notably fragile fruiting bodies that can disappear in as little as a few days (K. Nakasone, personal communication).

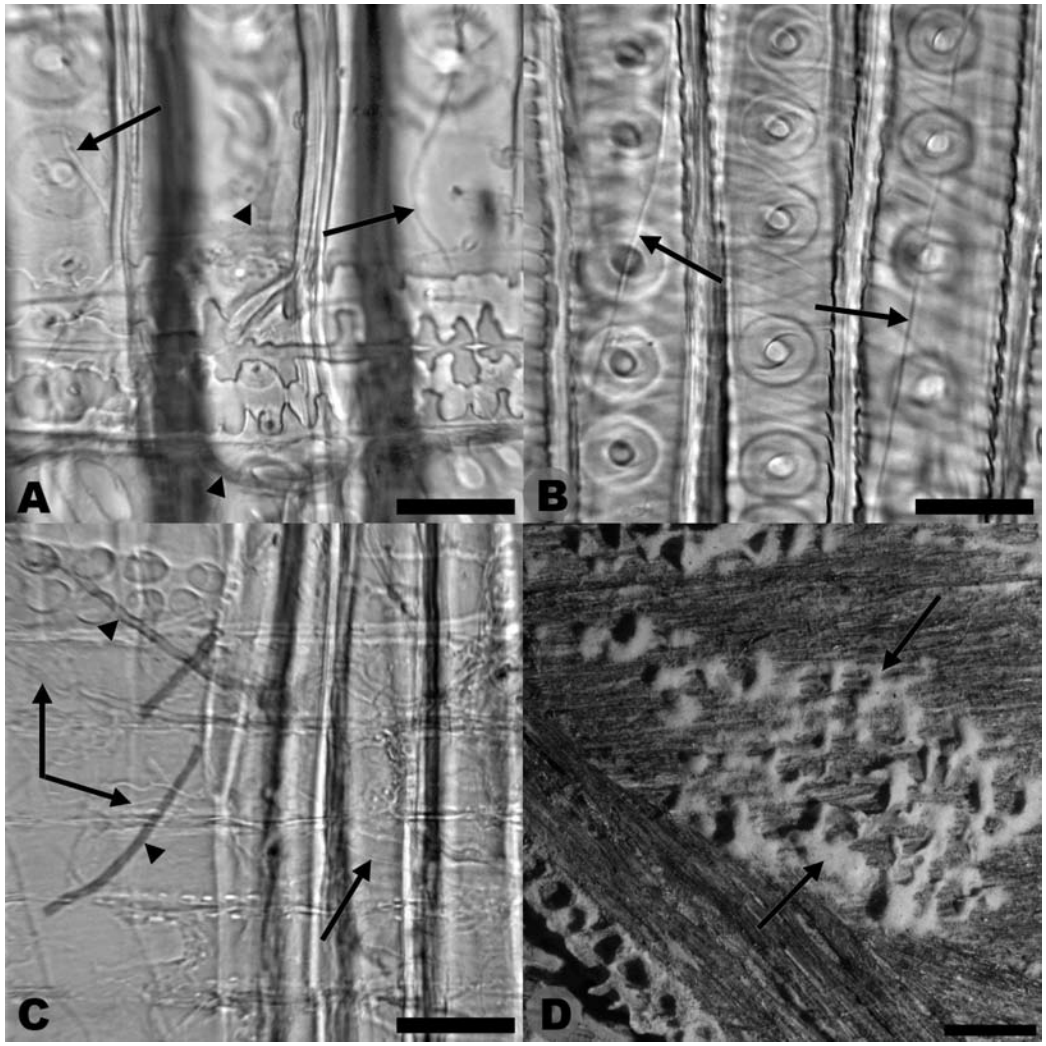

Figure 4: Light micrographs documenting the presence of fungi in or on panel products. **A–C**: Transmitted-light micrographs, scale bars represent 20 µm. Arrows indicate decay-type fungal hyphae; arrowheads indicate stain-type hyphae. A: SYP plywood specimen SP-68. B: Douglas-fir plywood specimen DF-76; stain-type hyphae are absent in this image. C: Aspen plywood specimen AS-68. Many more decay-type hyphae are not labeled. **D**: Stereophotomicrograph showing *Antrodia variiformis* growing on the surface of aspen OSB, OS-66. Arrows indicate portions of the raised fruiting body of the fungus. Scale bar represents 2 mm.

specimens broke and fell off the fence between May 1999 and October 2002. In October 2002, those specimens that remained on the fence, and were not removed at that time, were abandoned.

[11] Fungal fruiting between inspection times cannot be precluded.

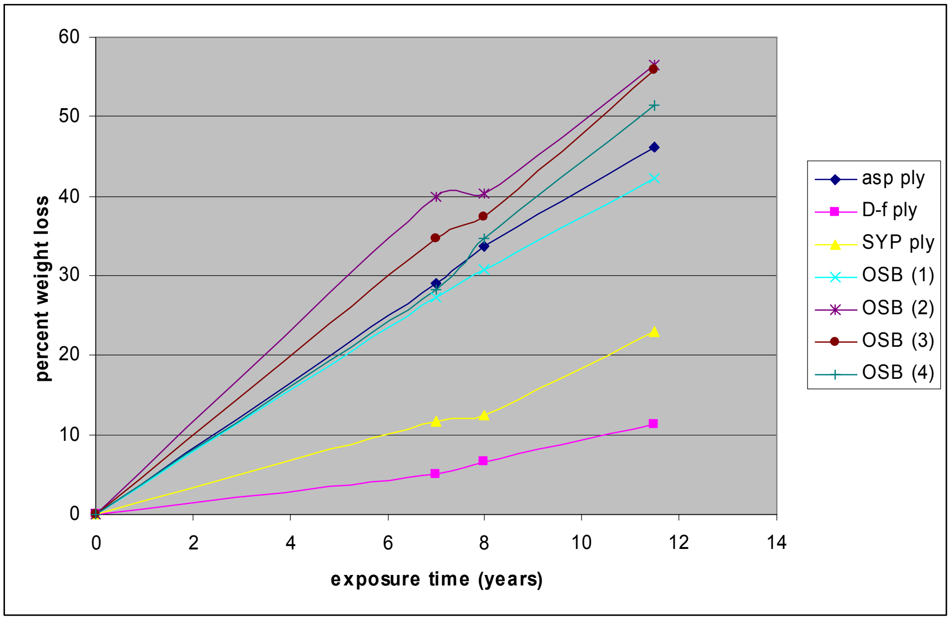

Figure 5: Estimated and measured weight loss as functions of exposure period

Weighing the reconditioned specimens removed from exposure at 11.5 years before testing in static bending permitted the determination of specimen weight loss during exposure. Unfortunately, specimens removed from exposure at shorter exposure times had not been weighed after reconditioning. Test specimens that had been removed from the fences at 7 and 8 years of exposure were still available in November 2002, and although they had been broken in static bending and end-trimmed, estimated reconditioned whole-specimen weights were calculated by adjusting each specimen's weight for its length. Figure 5 shows weight loss with exposure time (estimated losses at 7 and 8 years of exposure and known weight losses at 11.5 years). The time plots show progressive weight loss with exposure time for all panel types.

Panels fabricated from aspen showed more extensive weight losses than did panels fabricated from SYP or Douglas-fir, with SYP plywood showing proportionally more weight loss than Douglas-fir plywood. These observations concur with the observations of fruiting bodies made at 7 years of exposure, with the microscopic observations made at 7 and 8 years of exposure, with the findings of Laks et al.(2002), and with wood species decay resistance ratings in the *Wood Handbook* (FPL 1999). Some portion of the weight loss values plotted in Figure 5 is probably attributable to surface erosion. It should be noted, however, that the proportional weight losses of aspen, SYP, and Douglas-fir plywoods substantially exceed their proportional thickness losses at corresponding exposure times (Figure 1).

Discussion

As might be expected with relatively small (51 by 305 mm) test specimens, the mechanical properties of the sheathing grade plywood specimens (which randomly contained defects) sometimes showed appreciable variability. The specimens of aspen plywood had fewer and smaller knots in face veneers than did the specimens of Douglas-fir or SYP plywood. Descriptive

Table 3: Descriptive statistics for variation in mechanical property values at progressive exposure times in five-specimen samples of sheathing-grade plywoods

Material	Exposure time (years)	SD (MPa) (and COV, %) about mean MOR[a]	SD (MPa) (and COV, %) about mean MOE[a]
Douglas-fir plywood	1	9.2 (22)	813 (12)
	2	4.9 (15)	983 (17)
	7	16 (71)	2165 (72)
	8	8.5 (31)	1144 (28)
	11.5	3.1 (29)	1204 (44)
SYP plywood	1	2.6 (5)	878 (11)
	2	6.0 (14)	1084 (16)
	7	11 (42)	1014 (22)
	8	12 (47)	1328 (32)
	11.5	3.7 (63)	597 (21)
Aspen plywood	1	3.4 (10)	968 (19)
	2	4.8 (16)	699 (15)
	7	1.2 (8)	233 (11)
	8	1.0 (8)	256 (14)
	11.5	2.5 (48)	189 (21)

[a]SD, standard deviation; COV, coefficient of variation.

statistics for variation about mean MOR and MOE values for samples of five specimens removed from the test fence at progressive exposure times are shown in Table 3. The values indicate that variation in mechanical test data was consistently greater in samples of softwood (Douglas-fir and SYP) plywood specimens than in samples of aspen plywood specimens. Group *t*-tests indicated that the MOR and MOE values in the samples of Douglas-fir plywood at 7 years exposure were statistically indistinguishable from those in the sample at 8 years exposure at an alpha level of 0.05. One particularly knotty test specimen of Douglas-fir plywood substantially depressed the average mechanical property values at 7 years of exposure, and in turn was responsible for the apparent aberration in the mechanical property time trend plots (Figures 2 and 3) for Douglas-fir plywood between 7 and 8 years of exposure time.

Table 4 indicates that in this study, the commercial OSBs retained substantially lower proportions of their mechanical property values over time than did commercial (or laboratory-fabricated) flakeboards in the previous study (River 1994). We calculated decay hazard climate index values (Scheffer 1971) for the periods of the two studies from weather data for Madison maintained by the National Climatic Data Center. Higher index values are indicative of more conducive conditions for decay development; index values of 30 to 65 indicate intermediately favorable conditions for decay, whereas an index value in excess of 65 indicates a conducive climate for decay (Scheffer 1971). During the course of this study the climate at Madison was more conducive to decay of wood and wood products than it had been during the previous study (River 1994). In this study, the average annualized climate index value over the first 8 years of

Table 4: Comparative mechanical property retention values at extended exposure times

Study	Material	Exposure period (years)	Average climate index over exposure period	MOR retention (%)	MOE retention (%)
Current	Aspen OSBs	8	47.0	10–17	6–11
River (1994)	Aspen waferboards	10	42.0	28–30	17–18
River (1994)	Commercial coniferous strandboards	10	42.0	55–56	39–40
River (1994)	Laboratory-fabricated flakeboards (coniferous)	10	42.0	37–50	31–49
Current	Sheathing-grade Douglas-fir plywood	8	47.0	54	54
River (1994)	Marine-grade Douglas-fir plywood	10	42.0	49	55

exposure was 47.0; of the 24-month periods during that 8 years that began on April 1, the period with the highest index value was from April 1993 through March 1995, during which the annualized value was 61.3. In contrast, during the previous study (River 1994), the average annualized climate index was 42.0 over a 10-year period, and of the 24-month periods during that 10 years that began on April 1, the period with the highest index value was April 1986 through March 1988, during which the annualized value was 50.8. This suggests that the poorer retention of properties by flakeboards in this study was related, at least in part, to exposure conditions, although the possibility that the flakeboards in the two studies had inherently different decay resistances cannot be dismissed. All the flakeboards in this study were fabricated from aspen, whereas many of the flakeboards in the previous study were fabricated of wood raw material with relatively greater decay resistance. In addition, the flakeboards in this study had shown relatively greater propensity for thickness swelling (Okkonen and River 1996). Nofal and Kumaran (2000) reported that progressive thickness swelling in OSB is associated with progressively greater water absorbtivity. It is worth noting that contrary to the appreciable differences in property retention of flakeboards in the two studies, the property retention of sheathing-grade Douglas-fir plywood in this study was similar to that of marine-grade Douglas-fir plywood in the previous study (Table 4).

Conclusions

1. All panels included in this study retained substantially less than half their mechanical property values by 11.5 years of exterior exposure. The aspen OSBs retained virtually none of their mechanical property values by 11.5 years. The panels investigated in this study were marketed as Exposure 1 panels and behaved as such; they proved incapable of maintaining structural property values in prolonged exterior exposure.

2. Despite the fact that the sheathing-grade plywood panels showed substantial degradation in structural property values, they showed essentially no indication of veneer delamination. Degradation in mechanical property values was evidently dominated by other causal factors, such as surface veneer checking and erosion and wood decay.

3. All panels included in this study were infested by decay fungi by 7 years of exposure and beyond 7 years of exposure showed evidence of progressive degradation that would be consistent with the action of decay fungi. The infestation was most severe in panels fabricated from aspen, and during the course of the study these panels showed obvious outward indication of infestation, namely the (ephemeral) occurrence of fungal fruiting bodies. To our best knowledge, Douglas-fir plywood and SYP plywood did not show fungal fruiting bodies on their surfaces over the course of the study. Nevertheless, by 11.5 years of exposure, the Douglas-fir and SYP plywood specimens had experienced 11% and 23% weight losses, respectively; neither of these weight loss figures could be wholly attributed to surface erosion.

4. In this study, the conventional assumption that test fence exposures can be designed to induce moisture-cycling-induced stresses on adhesive bonds in specimens while simultaneously excluding infestation by decay fungi proved to be erroneous. The specimens in this study were designed and configured to undergo rapid moisture fluctuation. Although there is no evidence that the specimens in this study were infested by fungi that commonly decay wood products, there was clear evidence that all specimens were nevertheless infested and significantly degraded by decay fungi. The infestation was apparently by decay species that are adapted to infest wood that undergoes rapid moisture and temperature fluctuation.

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