RELATIONSHIP BETWEEN INCIPIENT DECAY, STRENGTH, AND CHEMICAL COMPOSITION OF DOUGLAS-FIR HEARTWOOD

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ABSTRACT

A new laboratory technique to simulate the initiation of wood decay and to assess the effects of incipient decay on material properties is described. Douglas-fir heartwood specimens were exposed to brown-rot (*Postia placenta* and *Gloeophyllum trabeum*) fungi for various periods. Bending properties were determined by nondestructive and destructive tests, and chemical composition of specimens was analyzed. Weight losses of 1 to 18% were linearly related to strength losses of 5 to 70%. Wood strength loss by brown-rot fungi was also closely related to degradation of hemicellulose components. Hemicellulose sidechains, such as arabinose and galactose, were degraded in the earliest stages of decay; main-chain hemicellulose carbohydrates, such as mannose and xylose, were degraded in the later stages. Changes in glucose content, a measure of residual cellulose, were minimal. Our technique was effective for establishing and assessing brown-rot decay.

Keywords: Decay, mechanical properties, wood chemistry, brown rot.

INTRODUCTION

The early stages of fungal decay are often characterized by dramatic decreases in some mechanical properties with only modest losses in wood components and minimal changes in appearance (Wilcox 1978). This early stage of decay, often referred to as incipient decay, is important in structural uses of wood because of the dangers posed by sudden failure of seemingly sound material. Detecting incipient decay and understanding the nature of the dramatic property changes have been extensively studied, but only a few studies have evaluated the effects of fungal attack on both strength and chemical properties (Scheffer 1936; Henningsson 1967; Green et al. 1991). Relatively few studies have evaluated the effects of fungal colonization on mechanical properties of Douglas-fir. Significant strength effects have been noted with both white- and brown-rot fungi using very small specimens exposed on agar or soil (Kennedy and Ifju 1962). However,

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the use of extremely small specimens may accentuate fungal effects because increasing the surface-to-volume ratio might artificially accentuate the significance of some fungi. This would be especially relevant in testing some fungi, such as soft-rot fungi, which may tend to initiate decay at the surface of the wood before progressing inward; therefore, such fungi might not be capable of significant wood colonization in the field.

Both the chemical composition and specific morphology of any wood species influence the rate of decay by any particular decay fungus (Scheffer and Cowling 1966). Hemicelluloses develop an encrusting envelope around cellulose microfibrils so that degradation and removal of depolymerized cellulose may depend on prior removal of hemicelluloses, particularly glucomannans (Highley 1987). Glucomannans are removed faster than xylose, and both types of hemicellulose are removed faster than cellulose (Kirk and Highley 1973). Differences in the ability of brown-rot and white-rot fungi to use hemicelluloses may explain why brown-rot fungi prefer softwoods to hardwoods (Keilich et al. 1970).

Historically, many laboratory studies of wood decay have utilized large quantities of fungal inoculum or a predecayed starter strip to establish the fungus in the tested wood. For example, in an ASTM D2017 soil-block test, the ratio of the volume of the predecayed feeder strip to the test block is 0.54 (3,045 mm^3/ 5,625 mm^3), which assures a massive fungal attack. In the natural environment, however, initial fungal colonization is often initiated by a limited number of spores or hyphal fragments. Thus, initial colonization can pose particular challenges to the fungus in wood species containing elevated quantities of extractives (Smith et al. 1992). Studies using large quantities of inoculum may obscure more subtle chemical interactions that might inhibit the colonization of the wood by decay fungi or artificially alter the rate of decay when compared to the rate of decay in the natural environment. At present, no single standardized laboratory test is available to assess strength, chemical, and weight losses associated with fungal colonization.

OBJECTIVE

The purpose of this study was to explore the relationship between incipient decay, strength, and chemical composition of Douglas-fir heartwood. To accomplish this, we developed a laboratory technique to simulate the initiation of wood decay in natural environments and to assess the effects of incipient decay on material properties. We used mycelial fragments of selected wood-degrading fungi to colonize wood microbeams and then subjected the beams to matched chemical and mechanical tests.

METHODS AND MATERIALS

Specimen preparation

A single, unseasoned, 4.2-m-long Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] log was obtained from a cut-off butt section of a freshly peeled pole. The 48-year-old log averaged 356 mm in diameter; the heartwood-sapwood boundary occurred at an average of 34 years, with a range of 31 to 36 years. Rate of growth was between 0.3 to 0.4 growth rings per millimeter.

Moisture content was checked using an electrical resistance moisture meter. Sapwood moisture content was estimated to be >30% at a 25-mm depth from the surface, and heartwood moisture content was estimated to be 28% at a 75-mm depth. Small, clear, 9.5- by 25.0- by 254-mm (radial by tangential by longitudinal) heartwood specimens, free of juvenile wood, were obtained. Sapwood was eliminated because of its susceptibility to decay; juvenile wood (defined as being within 12 growth rings of the pith) was eliminated because of its widely variable strength properties (Bendtsen et al. 1988). The presence of heartwood was confirmed by application of a 10% ferrous chloride solution (Kutscha and Sachs 1962).

Because oven-drying specimens before exposure and testing could affect resistance of the

heartwood to decay and subsequent strength test results, a noninfluential method was used to estimate initial moisture content (MC) and specific gravity (SG). To obtain this estimate, a 50-mm-long MC-SG block was cut from each freshly cut 254-mm-long specimen. The remaining 203-mm-long specimens were used for subsequent exposure and testing. The MC-SG blocks were oven-dried at 103 C for 48 h, measured, and weighed. Initial MC and SG for each 50-mm MC-SG block were then calculated and used as an estimate of the initial MC, predecay oven-dry weight, and SG for each 203-mm test specimen. These values were later used to estimate decay-induced weight loss.

Fungi

The brown-rot fungi used in the biological exposures were *Postia placenta* (Fr.) M. Larsen and Lombard) (Madison 698) and *Gloeophyllum trabeum* (Pers.:Fr.) Murr. (Madison 617). *Postia placenta* is a recognized destroyer of Douglas-fir; *G. trabeum* is a common isolate from coniferous wood exposed out of ground contact. The white-rot fungi used were *Trametes versicolor* (L:Fr.) Pilat (Madison R-105) and *Bjerkandera adusta* (Willd.:Fr.) Karst. *Trametes versicolor* is a commonly isolated fungi from most North American wood species; *B. adusta* represents a common isolate from southern pine utility poles (Zabel et al. 1985).

Biological exposure

Groups of 12 Douglas-fir 203-mm specimens were each randomly divided into subgroups of six specimens. Each subgroup was placed in western hemlock [*Tsuga heterophylla* (Raf) Sarg] sapwood rails (10 × 10 × 200 mm). The middle-third of each specimen, which rested between the rails, was covered with moistened vermiculite to confine decay within a length of the specimen that could be accurately evaluated in later mechanical tests (Fig. 1) (see section on destructive evaluation). Each subgroup of six specimens was then placed in an autoclavable bag with a small air-permeable membrane. Each bag received 60 g of vermiculite and 180 ml of a 0.5% aqueous malt extract. The bags were partially sealed and steam autoclaved at 121 C for 30 min. The bags were then immediately sealed to prevent contamination, cooled to room temperature, inoculated with the appropriate fungal-water suspension, and resealed. Fungal inoculum was prepared by growing each isolate in 100 ml of 2% malt extract for 7 to 14 days on a rotary shaker. The resulting mycelial mats were filtered and washed with distilled water. The mycelium was resuspended in sterile distilled water and aseptically blended to break up individual hyphae. One hundred milliliters of this inoculum were added to each bag.

The bagged specimens were incubated in the dark at 27 C and 65% relative humidity for predesignated periods. Incubation periods for the brown-rot fungi were 3, 34, 49, 84, 119, and 177 days; those for the white-rot fungi were 7, 35, 50, 85, 120, and 178 days.

Environmental conditioning

All specimens were removed from the biological exposure bags after their designated incubation time and dried to approximately 12% equilibrium moisture content (EMC) at 25 C/65% relative humidity to stop fungal activity before mechanical testing.

Nondestructive evaluation

Stress wave transit time is a nondestructive measure of modulus of elasticity (MOE) (Ross and Pellerin 1991). The MOE was assessed for each 203–mm specimen prior to mechanical bending by striking a small pendulum-type hammer to one end of the specimen and then monitoring the time for the stress wave to travel between two accelerometers mounted 20 mm from each end of the specimen (Ross and Pellerin 1991).

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FIG. 1. Method used to expose Douglas-fir heartwood specimens to decay fungi. Specimens were placed on western hemlock rails, covered with moistened vermiculite, and placed in a sealed autoclave bag with an air-permeable membrane. Specimens shown before (a) and after (b) removal from autoclave bag.


P. placenta
119 days
a


DA5L
DA5K
DA5J
DA5I
DA5H
DA5G
P. placenta
119 days
b

Destructive evaluation

Most previous studies of fungal-induced strength effects employed a simple three-point bending test in which the specimen rests on two supports and a load is applied at a single point in the center. In such a system, the maximum bending moment (force) produced in the beam increases consistently between the support and the load head and is only maximized directly under the load head (Fig. 2a). In the biological exposure method we developed, wood-destroying fungi may randomly initiate zones of decay over the 67-mm decay zone. Very early in the incipient decay process, these zones of decay may not coincide with the center of the test specimens. Thus, if a center-point load is used, the areas of maximum stress might not coincide with the location of a zone of decay. To address this problem, a four-point loading technique was used to produce a uniform maximum bending moment over the 67-mm decayed section of the beam located between the two central load-heads (Fig. 2b).

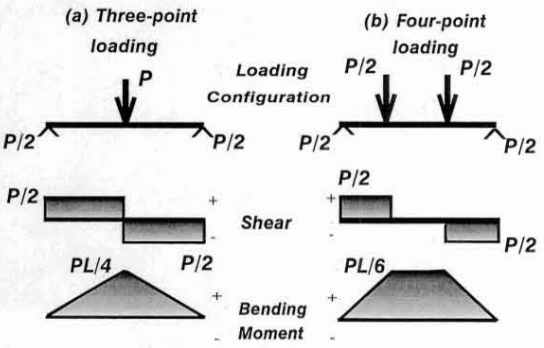

FIG. 2. Shear and bending moment diagrams for three-point (a) and four-point at L/3 (b) loading configurations where P is load and L is span.

Initially, a four-point loading configuration with a span of 133.4 mm and load-head span of 66.7 mm was employed to maximize the length of the constant-moment zone. However, preliminary testing showed that the load head configuration produced undesirable shear failures between the supports and the load head rather than the desired compression or tensile failure on the top or bottom surface between the load heads. Therefore, load head span was decreased to 63.5 mm, which was found to successfully dissipate the shear energy over a longer span by producing the desired compression or tensile type of failures between the load heads. The rate of loading was 1.25 mm/min, and time to failure averaged 4 to 5 min. All specimens were tested with the pith side up so that tensile stress was maximized on the face farthest from the pith. After testing, the entire specimen was oven-dried to obtain specific gravity (oven-dry weight/oven-dry volume) and moisture content.

Chemical analysis

The effects of fungal exposure on wood components were assessed by cutting a wafer approximately 25 mm long by full cross-section (9.5 by 25.4 mm) from within the decay zone near the point of mechanical failure of each specimen. This wafer was ground to 30 mesh (547 μm), and material was combined from each replicate at each fungal-exposure combination. A 50-mg portion of this ground sample was analyzed for carbohydrates using high pressure liquid chromatography (HPLC) procedures developed by Pettersen and Schwandt (1991). Klason lignin analysis was performed on another 50-mg portion of the ground sample (Effland 1977). Alkali solubility in 1% NaOH was measured following TAPPI Standard T-212 OM-83 (TAPPI 1988).

RESULTS AND DISCUSSION

Based on our visual observation of specimens in autoclave bags, biological activity apparently occurred with all four basidiomycetes tested. However, the activity of the two brown-rot fungi was far greater than that of the two white-rot fungi.

Both brown-rot fungi colonized most of the entire cross-section of the Douglas-fir test beams based on visual inspection of the resultant discoloration (Fig. 1b). However, both white-rot fungi successfully colonized only the surface of the test beams and had little visually apparent success in colonizing deeper than 0.5 mm into the wood. Under different conditions, we would expect the white-rot fungi to flourish. Based upon this visual examination, the brown-rot fungi appeared to be more capable than the

TABLE 1. *Changes in physical properties of Douglas-fir microbeams decayed by brown- or white-rot fungi after various incubation periods.*[a]

Fungus	Type	Incubation time (days)	Sample size	MOE (GPa)		MOR (MPa)		WML (kJ/m³)		EMC (%)	Stress wave (m/s)	Weight loss[b,c] (percent)
				Mean	SD	Mean	SD	Mean	SD			
P. placenta	Brown-rot	3	12	12.91	1.33	83.63	6.96	3.11	1.13	11.7	29.6	4.2
		34	12	12.26	2.30	79.07	15.68	2.64	1.16	11.9	30.0	2.7
		49	12	12.43	1.53	79.72	14.08	3.41	1.18	11.9	31.0	2.1
		84	12	10.60	1.80	62.88	13.03	2.05	0.86	11.9	30.5	7.4
		119	12	10.67	2.03	60.65	5.87	1.92	0.79	12.2	31.5	12.2
		177	12	7.32	1.34	33.16	8.18	0.53	0.18	12.7	35.1	19.8
G. trabeum	Brown-rot	3	12	12.71	2.01	87.39	16.33	2.73	0.95	11.8	29.9	2.5
		34	12	12.27	1.38	73.02	9.02	2.56	1.10	11.8	31.9	3.6
		49	12	12.74	1.07	76.99	5.47	2.97	0.98	11.8	29.0	7.0
		84	12	10.65	1.48	61.08	9.57	1.75	0.94	12.0	30.1	7.9
		119	12	10.56	2.21	53.10	10.73	1.06	0.45	12.0	31.5	11.5
		177	12	6.65	1.58	25.10	7.79	0.48	0.40	12.3	33.5	18.0
T. versicolor	White-rot	7	12	13.31	1.57	88.28	10.17	3.22	1.22	11.8	30.2	3.7
		35	12	13.33	1.28	85.19	8.88	3.29	1.41	11.5	30.0	5.2
		50	6	12.56	2.38	91.34	16.21	3.90	2.21	11.9	31.8	0.7
		85	12	13.22	1.55	85.26	9.86	2.91	1.60	11.7	30.5	4.8
		120	12	12.67	1.14	78.40	7.06	2.41	0.96	11.9	32.0	6.5
		178	12	13.84	1.71	87.86	6.54	3.70	1.44	12.2	33.3	2.5
B. adusta	White-rot	7	12	12.85	1.74	82.60	12.99	3.01	2.49	11.9	32.2	3.8
		35	12	13.59	1.55	89.17	9.41	2.69	0.86	12.0	31.3	2.6
		50	12	13.35	1.78	90.06	14.95	2.91	0.98	11.9	32.0	1.7
		85	12	13.08	1.15	86.09	6.93	3.25	1.19	11.9	32.4	5.1
		120	12	13.32	1.39	88.35	7.84	3.51	1.45	12.0	32.2	5.6
		178	12	14.24	2.04	87.44	7.74	2.97	0.96	12.0	30.9	4.1
(Control)	(Steam sterilized)		12	13.37	1.88	83.13	11.74	2.40	0.98	11.8	31.5	3.9
(Control)	(Untreated)		36	12.60	1.65	93.94	12.20	3.60	1.47	12.1	31.8	—

[a] MOE is modulus of elasticity, MOR modulus of rupture, WML work to maximum load, EMC equilibrium moisture content, and SD standard deviation.
[b] Basic specific gravity (oven-dry weight to oven-dry volume) of unsterilized controls = 0.468.
[c] Compared to unsterilized control.

white-rot fungi tested in colonizing the Douglas-fir heartwood beams, suggesting that the experimental materials and environmental conditions of the procedure tended to favor the brown-rot fungi.

Confining vermiculite and fungal inoculum to the middle-third of the beams appeared to successfully concentrate the decay area. This technique also enabled us to assess the progression of changes in chemical composition and strength throughout the entire period of incipient decay.

Wood properties

For each combination of fungus and incubation period, Student's *t*-tests were performed to determine if mechanical property results from one autoclave bag could be pooled or were different from the results from the second bag. At each combination, the Student's *t*-test assuming equal variance and the Cochran and Cox *t*-test approximation assuming unequal variances (SAS 1988) confirmed that for all three mechanical properties the results from the two separate autoclave bags were not found to be significantly different (<0.05). Thus, the results from the two bags were pooled at each fungus-incubation period.

Noninoculated, steam-sterilized specimens had slightly higher MOE values compared with noninoculated, unsterilized specimens; bending strength or modulus of rupture (MOR) and work to maximum load (WML), a measure of the energy required to cause failure, were re-

TABLE 2. *Results of Duncan's multiple comparison of the effect of incubation period (days) for each brown-rot fungus and mechanical property tested.*[a]

Fungus	Modulus of elasticity	Modulus of rupture	Work to maximum load
P. placenta	3 0 49 34 119 84 177	0 3 49 34 84 119 177	0 49 3 34 84 119 177
G. trabeum	49 3 0 34 84 119 177	0 3 49 34 84 119 177	0 49 3 34 84 119 177

[a] Incubation period(s) that were found to not be significantly different ($P \geq 0.05$) are underlined. Average values for each property-fungus-time combination can be found in Table 1.

duced by 12 and 33%, respectively (Table 1). This effect was slightly exaggerated because the specimens were small, but it appears consistent with results of previous studies on the effects of elevated temperature on mechanical properties (USDA 1987).

Steam sterilization alone accounted for a weight loss of roughly 4% ± 1% (Table 1). Thus, the early (≤50 days) weight losses evident with brown-rot fungi were probably merely a result of the steam sterilization process. However, noticeable brown-rot decay-induced weight loss was evident thereafter (Table 1). This slow initiation of decay allowed us to monitor the early stages of brown-rot decay at low-to-moderate weight losses for *P. placenta* and *G. trabeum*. During this time, the post-exposure EMC of the slightly decayed material steadily increased as the incubation period increased (Table 1). At higher weight loss (that is, >10%), brown-rot fungi generally decreased EMC as a result of the loss of noncrystalline cellulose (Cowling 1961). The increase in EMC found in our study may reflect the initial liberation of water-bonding sites within the carbohydrates and the lack of utilization of carbohydrate decomposition products during this early decay.

In general, brown-rot fungi had greater effects on destructively measured MOE, MOR, and WML than did white-rot fungi (Tables 1 and 2). Brown-rot fungi exerted only minimal effects on wood properties for the first 50 days. As colonization proceeded, however, *P. placenta* and *G. trabeum* were both associated with progressive reductions in MOE, MOR, and WML. Reductions in bending properties were approximately three to four times the corresponding wood weight-loss estimates (Fig. 3). These results seem to confirm previous findings that mechanical property changes provide a more precise measure of fungal decay than does weight loss (Scheffer 1936; Green et al. 1991). The results also support the well-known concept that for brown-rot decay, strength loss occurs faster than weight loss. However, these results show that strength loss does not occur without weight loss. Instead, they show that a significant linear relationship exists between strength loss and weight loss, even during the earliest stages of incipient brown-rot decay (Fig. 3).

Stress wave transit time slowly increased with incubation period, reflecting decreased nondestructively measured MOE. This suggests that given an adequate baseline, both strength and weight loss could be measured noninvasively during the course of biological exposure

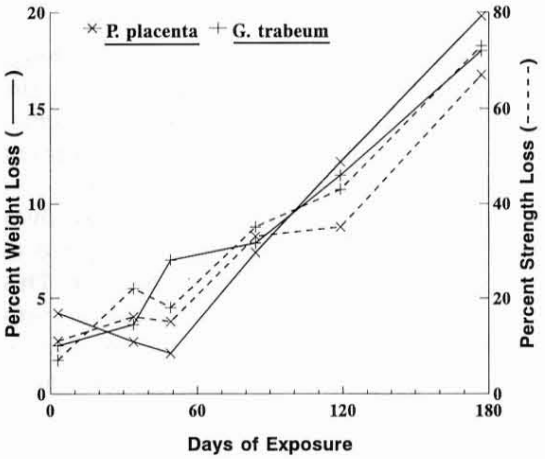

FIG. 3. Effects of two brown-rot fungi on wood weight loss and modulus of rupture of Douglas-fir heartwood microbeams.

TABLE 3. *Effects of decay fungi on chemical composition of Douglas-fir specimens.*

Fungus	Type	Incubation time (days)	Percentage of total chemical composition by weight[a]						
			Arabinan	Galactan	Glucan	Xylan	Mannan	Klason lignin	Solubility in 1% NaOH[b]
A. placenta	Brown-rot	3	1.0	3.1	46.9	3.9	13.9	30.2	11.2
		34	0.8	3.0	47.3	3.9	13.3	30.5	13.8
		49	0.8	3.8	46.4	4.2	12.5	31.6	14.2
		84	0.7	3.3	46.5	4.0	12.4	31.7	13.9
		119	0.7	2.9	47.0	3.8	12.8	31.0	17.0
		177	0.8	2.8	45.3	3.7	11.5	32.8	16.2
G. trabeum	Brown-rot	3	1.1	3.6	45.9	4.0	13.3	30.3	8.7
		34	0.8	3.2	44.1	3.9	12.6	31.3	13.6
		49	0.8	2.7	45.8	3.6	12.9	30.8	—
		84	0.8	2.9	45.0	3.6	12.4	31.5	16.8
		119	0.8	2.8	45.0	3.6	12.3	32.2	18.4
		177	0.7	2.2	43.4	3.3	10.6	34.9	24.2
T. versicolor	White-rot	7	1.1	3.5	46.8	4.3	13.4	30.6	12.4
		35	0.8	2.9	48.0	4.0	13.7	29.6	13.2
		50	0.8	3.9	47.0	4.5	13.7	31.0	12.4
		85	0.8	3.2	46.8	4.1	13.5	30.6	13.0
		120	0.8	3.4	46.9	4.2	13.4	31.1	12.4
		178	0.8	3.7	46.9	4.4	13.4	31.0	12.2
B. adusta	White-rot	7	1.1	3.2	46.7	4.1	13.4	30.5	12.5
		35	1.0	2.8	47.7	3.9	14.0	29.9	5.6
		50	0.7	3.5	46.6	4.1	13.3	31.0	13.9
		85	0.9	3.0	46.4	4.1	13.4	30.6	11.8
		20	0.7	3.0	47.3	4.2	13.6	30.8	10.9
		178	0.7	3.1	48.3	4.2	13.9	30.3	11.4
(Control)	(Steam sterilized)		1.0	3.2	46.0	4.0	13.3	30.4	11.0
(Control)	(Untreated)		1.4	4.1	45.6	4.0	12.8	32.0	11.8

[a] Pettersen and Schwandt (1991) report the average sensitivity of their HPLC method for ground solid wood to be ±0.1% for arabinan, ±0.1% for galactan, ±0.8% for glucan, ±0.2% for xylan, and ±0.2% for mannan.

[b] The coefficient of variation (COV) of this test was <25%. One group of NaOH solubility results was omitted because its COV was 0.80.

when using this laboratory technique by use of prewired stress-wave sensors with outside electrical leads.

White-rot fungi had no measurable effects on specific gravity or EMC and had only minimal effects on bending properties (Table 1). *Trametes versicolor* visually colonized the surface of the test beams, but had only minimal effects on chemical composition or destructively measured bending properties. *Bjerkandera adusta* did not appear to colonize the test beams to any significant extent. Although white-rot fungi are more prevalent on hardwoods, both of the fungi tested are among the fungi most commonly isolated from Douglas-fir or southern pine utility poles sampled in service (Zabel et al. 1980, 1985). Although *T. versicolor* and *B. adusta* are capable of colonizing Douglas-fir heartwood, our results suggest that these fungi had only minimal effects on structural components under our test conditions. Alteration of exposure conditions, such as the addition of exogenous nutrients or moisture, might increase the impacts of white-rot fungi, but these conditions are probably unlikely to occur in wood in service.

Chemical composition

Steam sterilization had minimal effects on chemical composition of the specimens, although galactose content decreased by 20% (Table 3). As expected from mechanical tests, brown-rot fungi were associated with more substantial changes in chemical composition.

Alkali solubility of specimens colonized by either of the two brown-rot fungi gradually increased with longer incubation periods, reflecting a general degradation of complex sugars in the wood at a faster rate than they can be metabolized by the fungi (Table 3). The white-rot fungi evaluated had no effect on alkali solubility, reflecting their general failure to initiate significant decay and their tendency to then utilize carbohydrates at about the same rate as they are released.

The percentage of arabinose declined slightly for both brown- and white-rot fungi, whereas galactose, glucose, xylose, and mannose levels declined only with brown-rot fungi (Table 3). These effects were noted after 50 days of incubation, corresponding to the decreases in mechanical properties noted with the brown-rot fungi. These changes suggest that the test fungi required some lag period before significant fungal colonization and hence wood degradation occurred. Related studies of Douglas-fir heartwood inoculated with *P. placenta* through a single hole drilled near the center of the beam produced measurable, but variable, losses in compression strength in about 1 month (Smith et al. 1992).

During the first 34 days of incubation, *P. placenta* utilized about 20% of the aribinose but none of the other wood components (Table 3). Incubation for an additional 15 days resulted in the loss of approximately an additional 10% of the arabinose and about 10% of the galactose and mannose. At the same time, alkali solubility increased, reflecting increasing solubilization of wood polysaccharides. *Gloeophyllum trabeum* removed 20% of the arabinose and 10% of the galactose and xylose during the first 34 days of incubation. No additional decreases in the relative percentages of arabinose were noted upon prolonged incubation; however, galactose, mannose, xylose, and glucose were removed to varying degrees. Alkali solubility of wood colonized by *G. trabeum* rose from 8.7 to 24.2% during the 177-day incubation period, suggesting a high rate of carbohydrate decomposition. Klason lignin content of specimens colonized by either *G. trabeum* or *P. placenta* apparently increased during the 177-day incubation period. Mitchell et al. (1953) showed this apparent increase in lignin to be merely a remnant of the systematic decrease in holocellulose. Thus, the general trend of a lack of effect on lignin by brown-rot fungus reflects the inability of these fungi to utilize lignin, whereas lignin contents of specimens exposed to *B. adusta* and *T. versicolor* remained proportionally constant with carbohydrate components.

Douglas-fir hemicelluloses contain twice as many glucogalactomannans as arabinoglucuronoxylans (Pettersen 1984) and have a mannose to glucose ratio of about 3:1 in the hexose hemicelluloses (Sjostrom 1981). Our results suggest that both brown-rot fungi aggressively degraded hemicellulose sidechains. Later in the incipient decay process, these fungi degraded the glucomannan mainchain. Many previous studies have suggested that hemicelluloses, because of their accessibility to enzymatic attack, are initially utilized by decay fungi (Highley 1987; Keilich et al. 1970; Kirk and Highley 1973). Our quantitative results support these previous studies.

Recent studies have explored the basic mechanisms of biological and thermal-chemical degradation of softwoods. These studies have revealed that attack by brown-rot fungi in the initial stages is an organic (oxalic) acid-mediated phenomenon (Green et al. 1991), while LeVan et al. (1990) found that initial thermal-chemical degradation of fire-retardant-treated wood is a mineral (phosphoric) acid-mediated phenomenon. These studies agree with our findings in that the initial mechanisms of attack by brown-rot fungi (Green et al. 1991) and by fire-retardant treatments when exposed to elevated temperatures (LeVan et al. 1990) are similar: these mechanisms are initially characterized by degradation of the hemicellulose sidechains followed by degradation of the hemicellulose mainchain.

Both white-rot fungi tested had minimal effects on chemical properties of the wood, although about 20% of the arabinose was removed after 35 or 50 days of exposure to *T. versicolor* or *B. adusta,* respectively. No evidence of degradation of other components, in-

cluding Klason lignin, was evident, even after 178 days of exposure. The limited attack of hemicellulose sidechains suggests that these fungi were only beginning to colonize and utilize the wood substrate. Longer exposures, different environmental conditions, or additives to stimulate fungal growth might be necessary to induce significant changes in chemical content of Douglas-fir exposed to white-rot fungi. The relative lack of effect associated with these fungi highlights the complex character of decay and raises perplexing questions as to the ecological role of the white-rot fungi in destroying coniferous wood, although white-rot fungi are often isolated from weathered coniferous heartwood under a variety of environmental field conditions.

Relationship between strength and chemical composition

Strength losses around 10% were noted with the two brown-rot fungi over the same period that arabinose and galactose removal occurred. Strength losses approached 60 to 70% as the glucomannans and xylan mainchains of the hemicelluloses were degraded. Previous studies noted significant strength losses with minimal weight losses (Wilcox 1978). Our results suggest that the relationship between strength and weight losses is difficult to measure, but nevertheless linear (Fig. 3). It is interesting to note that glucose concentration, as a gross measure of cellulose utilization, was reduced only slightly over the exposure period, while strength losses increased dramatically. Although depolymerization of cellulose by the decay fungus probably accounts for some strength loss, our results clearly show that a significant portion of the initial effect of brown-rot fungi on wood strength occurs as a direct result of hemicellulose decomposition.

CONCLUSIONS

Degradation of hemicellulose components was closely related to wood strength losses. These results show that hemicellulose plays a significant role in initial wood strength loss. The results also clearly show that strength loss and weight loss for brown-rot decay are linearly related.

Laboratory simulation of wood decay in natural environments (i.e., primarily through spore development and hyphal fragments rather than through the use of predecayed feeder strips) was found to be effective for brown-rot decay. Many improvements are needed to successfully develop a technique capable of studying a wide range of combinations of wood species, fungal species, and environmental conditions. The concept of concentrating fungal colonization in the middle-third of the test beam, which can then be easily tested in a four-point loading system, was successful. Further studies are needed to delineate more optimum environmental conditions or wood species conducive for growth of the white-rot fungi *Trametes versicolor* and *Bjerkandera adusta* or to select alternative white-rot fungi more capable of growth in Douglas-fir heartwood.

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