FUNGI COLONIZING REDWOOD IN COOLING TOWERS: IDENTITIES AND EFFECTS ON WOOD PROPERTIES[1]

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ABSTRACT

Heartwood from coastal redwood [*Sequoia sempervirens* (D. Don.) Endl.] is very durable and is often used untreated in harsh environments, such as cooling towers of power or chemical processing plants. Wood in this environment is often attacked by soft rot fungi. Some wood users attempt to bolster protection by including additives, such as chromium, in the water. Examination of sections cut from a redwood cooling tower revealed that most pieces were colonized by a variety of Fungi Imperfecti, in spite of surface chromium levels that averaged 0.26 lb/ft^3. Eleven species were isolated from the material; soft rot tests of these fungi indicated that all of the isolates were capable of causing Type 2 soft rot attack (cell-wall erosion). These fungi caused little or no weight loss on redwood specimens, but did damage less durable ponderosa pine sapwood. The results suggest that the redwood cooling tower was colonized by a variety of fungi; however, the combination of redwood extractives and a shallow chromium barrier appears to protect against soft rot attack.

Keywords: Redwood, cooling tower, soft rot decay, *Sequoia sempervirens*, *Phialophora*, breaking radius, longitudinal compression strength.

INTRODUCTION

The environment in cooling towers of power plants and chemical-processing facilities is too harsh for many basidiomycetous decay fungi. However, Basidiomycetes can cause internal decay in nonflooded zones (Song and Trulear 1986), and certain Ascomycetes and Fungi Imperfecti can cause soft rot of wood surfaces exposed to continuous wetting (Findlay and Savory 1950). Wooden cooling towers in the United States generally are constructed with naturally durable coastal redwood [*Sequoia sempervirens* (D. Don.) Endl.] (Clark and Scheffer 1983), although preservative-treated Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] and southern pines (*Pinus* spp.) are used in some areas. While redwood has performed well in most cooling-tower environments, some users have provided added protection by incorporating additives, including chromium, into the circulating water. These additives control corrosion and slime build-up, but their effect on fungal attack is unclear. Heartwood from old-growth redwood is extremely resistant to preservative penetration; however, any chromium that enters this zone is strongly bound to the wood (Hartford 1986) and, in combination with heartwood extractives, may present a shallow "barrier" to fungal attack.

The effect of this chromium/heartwood "barrier" on fungal colonization was examined on redwood members removed from a 30-year-old cooling tower. Wood strength (as compression strength and modulus of elasticity) in portions of this tower was low, and the operators were concerned that soft rot fungi were contributing to this decline.

<div align="center">MATERIALS AND METHODS</div>

Eight blocks (8.75 × 8.75 × 10 cm) were cut from redwood beams in the counterflow cooling tower of a chemical-processing plant. The beams had been in service for at least 10 years and had been subjected to temperatures from 35 C to 57 C; most were subjected to temperatures ranging from 35 to 50 C. Blocks were removed both from wood in continuous contact with water and from wood that was splashed intermittently.

Sections from these blocks were examined for residual chromium content by grinding samples on a Wiley mill to pass a 40-mesh screen and analyzing the ground samples for chromium on an Asoma Model 8010 X-ray fluorescence analyzer. These values were expressed as pounds of chromium (as CrO_3)/ft^3 of wood.

Isolating fungi

Plugs (3.0-cm long × 1.25-cm diameter) were removed from all four treated faces. The plugs were segmented into zones corresponding to 0 to 0.6, 0.6 to 1.8, and 1.8 to 3.0 cm from the surface. Nine small chips (1 mm square) were cut from each segment, surface-sterilized by brief flaming, and placed on acidified (pH 3.8–4.0) 1% agar containing 2% malt extract. The plates were incubated at room temperature for 30 days. Any fungi growing from the wood were subcultured onto fresh malt-extract plates to obtain pure cultures. All fungi isolated were tentatively identified from mycological keys (Raper and Thom 1949; Wang 1965; Barron 1968; Ellis 1971, 1976; Cole and Kendrick 1973).

Two methods were used to examine the ability of fungi isolated from redwood to reduce wood weight and strength. In each, a representative of each species isolated was tested. Where numerous isolations of the same species were made, two or three were tested to ensure that isolate variation did not cause us to omit a significant decayer.

Decay testing of redwood

The selected isolates first were tested by a vermiculite burial test (Nilsson 1973) for the ability to reduce weight and strength of blocks of redwood heartwood. To simulate leaching of wood extractives that might occur in cooling towers, test blocks (1.0 × 2.0 × 2.0 cm) were boiled in distilled water for 2 h. Glass jars (113.5 ml) were filled with 2 g of vermiculite on which was placed a 1-cm square of filter paper. Two redwood blocks were oven-dried, weighed, and added to each chamber; an additional 2 g of vermiculite was added, and a second 1-cm square of filter paper was placed on top. Twenty-five ml of nutrient solution (Nilsson 1973) were added, and the chamber was capped and autoclaved for 45 min at 121 C.

After cooling, each chamber was inoculated with an agar disc (2-mm diameter) cut from the edge of an actively growing culture of the test fungus. Each of 17

isolates, representing 10 species, was tested on 10 leached and 10 unleached blocks. The chambers were incubated at 28 C for 10 weeks, disassembled, and examined for evidence of colonization. The blocks were removed, scraped clean, oven-dried for 24 h, and weighed to determine weight loss during fungal exposure. Similarly treated blocks that had not been exposed to fungi were used for comparison. A small corner of each block was removed and examined microscopically for evidence of soft rot.

The test blocks were soaked to moisture levels above the fiber saturation point ($\sim 30\%$ moisture content), and the longitudinal compression strength (compression parallel to grain, LCS) was tested in an Instron Universal Testing Machine at a head speed of 0.2 cm/minute (Smith and Morrell 1987). Data were recorded continuously, but results were evaluated only at 3.0-mm compression and at maximum load. Longitudinal compression strength was chosen because this property is extremely important in cooling towers.

Decay testing of ponderosa pine

In the second set of tests, the ability of the isolates to cause soft rot was evaluated under more accelerated conditions. Ponderosa pine (*Pinus ponderosa* Doug. ex Laws.) sapwood, which is readily susceptible to biological attack (Scheffer and Cowling 1966), was the test medium.

To test weight loss, 2 g of vermiculite were added to each 57-ml bottle, followed by 2 oven-dried, weighed pine blocks (1.0 × 2.0 × 0.03 cm) and an additional 1.5 g of vermiculite. Filter paper (0.5 cm²) was placed on top, 12 ml of nutrient solution were added, and the chambers were capped and autoclaved 45 min at 121 C. After cooling, the chambers were inoculated and incubated in the same manner as the redwood test blocks. The chambers were then disassembled and the blocks oven-dried and weighed.

The ability of the isolates to induce mechanical damage was examined using ponderosa pine sapwood wafers (0.6 × 7.5 × 0.12 cm). Soft rot attack is frequently a surface phenomenon, and these wafers exposed a large surface to potential damage. Screw cap vials (21 × 70 mm; 14.7 ml) were partly filled with vermiculite, one wafer was inserted vertically, and vermiculite was added to cover the wafer. Filter paper (0.5 cm²) was placed on top, 5 ml of nutrient solution were added, and the chambers were capped and autoclaved 45 min at 121 C. Each isolate was inoculated into 30 chambers and incubated at 28 C for 10 weeks. The wafers were removed and oven-dried (54 C) overnight prior to testing. Each veneer was tested for bending toughness with a breaking radius test (Safo-Sampah and Graham 1976), in which the wafers are bent around mandrels of decreasing diameter until the wafers fail. This breaking radius can be related to the toughness of the veneer. Toughness tests are extremely sensitive to small changes in wood strength and can be good indicators of early decay.

RESULTS AND DISCUSSION

Chromium content of wood

X-ray fluorescence analysis of the outer zone of the test pieces indicated that the average chromium content of the wood was 0.26 lb/ft³. For aboveground exposures, the recommended retention level for treatment with chromated copper

TABLE 1. *Identity and isolation frequency of microfungi from chromium-treated redwood cooling towers.*

	Fungal frequency[1]						Percent frequency (total)
	Cooling tower beam						
Fungal species	1	2	4	5	6	8	
Phialophora richardsiae	22	12	61	—	59	15	26.08
Phialophora melinii	50	71	25	—	—	2	22.84
Paecilomyces variottii	—	—	—	4	9	49	9.57
Phialophora bubaki	—	—	—	48	5	—	8.18
Phialophora sp. C	—	—	3	19	—	—	3.39
Phialophora sp. A	4	7	1	—	—	—	1.85
Penicillium tardum	—	7	—	—	—	—	1.08
Alternaria alternata	1	—	—	—	1	—	0.30
Aspergillus niger	—	—	1	—	—	—	0.15
Epicoccum nigrum	—	—	—	—	—	1	0.15
Aureobasidium pullulans	—	—	—	—	—	1	0.15

[1] Expressed as number of occurrences in 108 isolation attempts. Percent frequency (total) is based upon 648 isolation attempts.

arsenate Type C, which contains 47.5% chromium (as CrO_3), is 0.25 lb/ft^3 (AWPA 1986). Immersion in chromium solutions effectively protects redwood specimens from weathering and fungal attack (Feist 1979; Williams and Feist 1985); chromium bound to the wood may perform a similar function in cooling towers.

Fungal isolates

No fungi were isolated from samples of two of the redwood beams. These boards were in the hottest zone of the tower (57 C) and were sprayed annually with sodium pentachlorophenate (Steven Blue, Martin Marietta Energy Systems, personal communication). It is unclear whether elevated temperature or chemical treatment prevented colonization. Eleven species were isolated from the remaining six beams; no species was present in all test pieces (Table 1). Five species were members of the genus *Phialophora*, which contains many species capable of soft rot attack (Nilsson 1973, 1978). Two of these species, *P. richardsiae* and *P. melinii*, were most commonly isolated and were present in all but one test piece. Both species cause both Types 1 and 2 soft rot damage (Nilsson 1973). (Type 1 damage appears as diamond-shaped cavities; Type 2 damage, as cell-wall erosion.) Very few nondecay fungi were isolated. Their absence may have resulted from the continuous wetting that leached most free sugars from the wood, leading to selection of fungi that degrade wood to obtain energy. The chromium barrier also may have excluded fungi from the wood.

Decay tests of redwood

Leached redwood blocks exposed to the test fungi lost relatively little weight and LCS (Table 2), suggesting that these fungi had little impact on the test blocks. The small amount of attack on the redwood specimens under test conditions is not surprising, considering the natural durability of this species. In the more dynamic cooling tower environment, the extractives normally present in redwood heartwood can leach away, possibly permitting more abundant fungal colonization.

TABLE 2. *Weight loss and longitudinal compression strength (LCS) of leached redwood blocks after exposure to fungi isolated from chromium-treated redwood.*[1]

Fungal species	Isolate	Weight loss (%)	Longitudinal compression strength[2] (kg)
Phialophora richardsiae	A	1.06 a	350 abc
Control		0.84 ab	344 abc
Phialophora melinii	A	0.76 ab	335 ab
Phialophora sp. C	A	0.73 abc	352 abc
Paecilomyces variottii		0.71 abc	345 abc
Penicillium tardum		0.61 abc	351 abc
Phialophora richardsiae	B	0.50 abc	380 e
Alternaria alternata		0.44 abc	355 bdc
Epicoccum nigrum		0.43 abc	354 bdc
Phialophora bubakii	A	0.22 bc	344 abc
Phialophora melinii	B	0.16 bcd	337 ab
Aspergillus niger		0.15 bcd	359 cd
Aureobasidum pullulans		0.15 bcd	348 abc
Phialophora sp. A	A	0.08 bcd	332 a
Phialophora bubakii	B	0.02 cd	355 bcd
Phialophora sp. A	B	−0.50 de	360 cd
Phialophora melinii	C	−0.58 e	371 de
Phialophora sp. C	B	−0.91 e	343 abc

[1] Leached blocks were boiled for 2 h to simulate long-term cooling tower exposure.
[2] Each figure is the average of 10 replicates. LCS is the value at maximum load. Numbers followed by the same letter in each column are not significantly different by the Newman-Keuls method for separating means.

Decay tests of pine

Exposure to *Phialophora melinii* caused significant weight losses in wafers and blocks of ponderosa pine sapwood (Table 3). Microscopic examination revealed that most of the fungi eroded the cell wall (Type 2 damage). Erosion is by far the more common type of soft rot (Nilsson 1973), and it is not surprising that our isolates produced this type of attack. Only four isolates (*Phialophora melinii*, *P. richardsiae*, *Paecilomyces variottii*, and *Penicillium tardum*) produced Type 1 soft rot in our test.

Although weight losses were generally low, several isolates caused slow Type 2 erosion and could influence wood properties over a long period. However, the combination of heartwood extractives and chromium fixed to the wood surface probably would minimize this impact in the original habitat of these fungi.

Many isolates that caused insignificant weight losses in the burial test did cause microscopically observable erosion and changed breaking radius substantially (Table 3). Toughness bending tolerance has been reported to be highly sensitive to the early stages of decay, when weight losses may not yet be apparent (Safo-Sampah and Graham 1976).

CONCLUSIONS

A variety of fungi capable of causing soft rot damage colonized the chromium-treated redwood, except in zones having elevated temperatures and annual sodium pentachlorophenate treatments. Many of these fungi caused slight weight losses, Type 2 soft rot damage, or both on ponderosa pine in laboratory decay tests, and 10 fungi reduced breaking radius strength below that of the control. These same fungi had little effect on redwood heartwood samples in similar decay tests. The

TABLE 3.   *Soft rot damage by fungi isolated from chromium-treated redwood as measured in ponderosa pine sapwood by a vermiculite burial test.*

Species	Isolate	Weight loss (%)	Breaking radius[1]	Soft rot type[2]
Chaetomium globosum[3]		14.60 a	6.27 a	1
Phialophora melinii	C	8.37 b	4.80 b	1
	A	7.76 b	4.97 b	1
Phialophora sp. C	B	6.07 c	3.48 efg	2
Alternaria alternata		5.85 c	3.96 cde	2
Paecilomyces variottii		5.83 c	4.01 cd	1, 2
Epicoccum nigrum		5.82 c	3.63 cdefg	2
Aureobasidium pullulans		5.57 c	3.18 g	2
Phialophora sp. C	A	5.41 c	3.91 cde	2
Phialophora melinii	B	5.08 cd	3.86 cde	2
Phialophora bubakii	B	5.02 cd	3.88 cde	2
Penicillium tardum		5.00 cd	3.61 cdefg	1, 2
Aspergillus niger		4.93 cd	3.63 cdefg	2
Phialophora bubakii	A	4.83 cd	3.73 cdef	2
Phialophora richardsiae	A	4.73 cd	4.17 c	1, 2
	B	4.44 cde	3.81 cde	2
Control		4.20 cde	3.25 fg	—
Phialophora sp. A	B	2.81 de	3.50 defg	2
	A	2.67 e	3.45 efg	2

[1] Numbers represent means of samples for weight loss and breaking radius. Numbers followed by the same letter are not significantly different by the Newman-Keuls method for separating means.
[2] Type 1 soft rot damage appears as diamond-shaped cavities; Type 2 damage is cell-wall erosion.
[3] Known soft rot fungus, used as a reference standard.

results indicate that, while many fungi can colonize chromium-treated redwood, their effects are minimal.

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