BIOCIDE PROTECTION OF FIELD-DRILLED BOLT HOLES IN RED OAK, YELLOW-POPLAR, LOBLOLLY PINE, AND DOUGLAS-FIR

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ABSTRACT

Field-drilling of holes in treated wood products sharply reduces the effectiveness of the original wood treatment, but most fabricators dislike the oily nature of the chemicals available for treating this damage. The ability of selected alternative water- and oilborne preservatives to protect simulated bolt holes was explored in a laboratory trial using Douglas-fir heartwood, red oak, yellow-poplar, and loblolly pine. The test methodology produced poor results with water-based chemicals because of the severe leaching treatment used, but was a reasonable predictor of the field performance of oil-based materials. Copper-8-quinolinolate (Cu-8) appeared to be the best oilborne material evaluated, whereas boron provided protection when leaching was not severe.

Wood preservatives provide excellent barriers against degradation by fungi, insects, and other agents, but performance can be sharply influenced by the integrity of this barrier (2). Although most specifications recommend that all cuts, bore holes, or other fabrication be performed before preservative treatment (1), later fabrication in the field can compromise the treatment barrier. This is particularly true in timber bridges, when members are cut to fit in decks, spikes are driven to attach decking, or holes are drilled to attach railings and other fixtures. Untreated wood can then be exposed, diminishing the benefits of preservative treatment and creating the potential for internal deterioration.

Standard M1 of the American Wood-Preservers' Association recommends that all cuts or other damage to the treated shell be supplementally treated with preservative solution. Often, however, these treatments are omitted because the workers dislike the oily nature of those chemicals. In addition, the applicator must be certified to apply pesticides because some topical treatments have restricted-use classifications. It is highly unlikely that fabrication damage will be treated because it is generally difficult to inspect a bridge to ensure that these treatments have indeed been performed.

Failure to treat field cuts and bore holes can sharply reduce service life and increase long-term maintenance costs of treated wood. Alternative, easy-to-apply treatments are needed to protect field-damaged wood from degradation. Unfortunately, lengthy field tests are needed to identify materials that will inhibit the development of decay. Morrell et al. (6) showed that more than 10 years were required to adequately test treatments of field-drilled bolt holes in Douglas-fir poles. Given the time constraints of field trials, we chose a laboratory assessment of the efficacy of selected chemicals on wood species used in timber-bridge construction.

The simplest approach is to measure weight loss in blocks treated with the desired chemical and exposed to a decay fungus, but the large size of the test blocks needed to realistically assess topical treatments may mask poor performers (7). Instead, we evaluated the ability of the test fungus to penetrate the surface chemical barrier and become established within the test block.

MATERIALS AND METHODS

Straight-grained, defect-free dimension lumber of red oak (*Quercus rubra* L.), yellow-poplar (*Liriodendron tulipifera* L.), loblolly pine (*Pinus taeda* L.), and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) was cut into blocks 25 by 50 by 38 mm long. One 10-mm-diameter bolt hole was drilled through each block at the center of the wide face. The blocks were then cut in half through the hole to create two 25- by 25 by 38-mm-long

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TABLE 1. –Treatments applied to conifer and hardwood blocks.

Chemical	Concentration	Carrier	Supplier
	(%)		
Sodium octaborate tetrahydrate (DOT)	10.0	Water	U.S. Borax, Valencia, Calif.
Sodium fluoride (NaF)	10.0	Water	Osmose Wood Preserving, Buffalo, N.Y.
Copper-8-quinolinate (Cu-8)	0.5 (as Cu)	Oil (toluene)	Morton Chemical Intl., Andover, Mass.
Copper naphthenate	2.0 (as Cu)	Oil (toluene)	OMG Inc., Cleveland, Ohio
Pentachorophenol (penta)	10.0	Oil (toluene)	ISK Biosciences, Memphis, Tenn.

pieces. Matched block halves were labeled, secured with a rubber band, and dip-treated for 3 minutes with selected fungicides or water to simulate treatment of a field-drilled bolt hole **(Table 1).** The blocks were then weathered for 0, 2, 4, or 8 weeks to monitor leaching. Weathering consisted of 0, 14, 28, or 56 cycles, respectively, of soaking the blocks in an excess of water for 8 hours, then oven-drying them overnight at 56°C. The blocks were then pressure-soaked with water, placed in a tray, and sterilized by steaming for 1 hour at 110°C.

The blocks were then exposed to the test fungus *Gloeophyllum trabeum* ((Pers.:Fr., Murrill); Isolate #ATCC 11539) by modifying a procedure from Sexton et al. (9). The inoculum was prepared by cutting a 3-mm-diameter plug from the edge of an actively growing culture of the test fungus on 1 percent malt-extract agar (MEA). The plug was incubated in 50 mL of 1.5 percent malt-extract broth for 14 to 21 days. Afterward, the mycelial growth was filtered and rinsed three times with sterile distilled water (dH_2O), then washed into a sterile container and diluted with 100 mL sterile dH_2O. The resulting inoculum suspension was briefly mixed in a blender. Inoculum viability and purity were confirmed by placing an aliquot on an MEA plate and observing regrowth of the test fungus and contaminants.

Approximately 180 g of dry vermiculite and 700 mL of H_2O were added to plastic bags, each with a breathable air patch. The bags were loosely sealed and autoclaved for 25 minutes at 121°C. The blocks were inoculated with the test fungus by injecting 200 µL of the mycelial suspension in sterile dH_2O into the inner surface of each bolt hole.

A sterile, galvanized bolt was placed in each hole, and a sterile nut was attached. The assembled blocks were placed in the sterile vermiculite, five blocks of a single treatment per bag, so that the wood was surrounded by vermiculite. The bags were sealed and incubated at 28°C for 2, 4, 6, or 8 weeks. At each time point, five blocks in a single bag from each treatment were removed. Although removing a single block from each bag would have been more statistically valid, each entry into the bag increased the risk of introducing contaminating flora. A series of four 4- to 5-mm-thick sections were cut, parallel to the grain direction, from each side of the bolt hole. Each section was cut into four 12.5- by 19.0-by 5-mm pieces, which were plated on 1.5 percent MEA and observed over 30 days for growth of the test fungus to measure chemical efficacy. Growth of the test fungus was distinguished by its yellowish mycelium. Where necessary, the resulting mycelial growth was examined microscopically for characteristics typical of the test fungus. The percentage of wood pieces from which the test fungus grew was used as a measure of wood colonization at a given distance from the bolt hole.

RESULTS AND DISCUSSION

Topical preservatives can be excellent barriers against fungal attack, but many of our treatments were susceptible to leaching **(Tables** 2 through **5).** While biocide mobility may be advantageous when the biocide can move to the point of fungal attack, this is eventually detrimental because such materials are more likely to be depleted in these areas. This is a particular problem with bolt-hole treatments because it is difficult to retreat the damaged wood.

Fungal colonization in untreated control blocks generally increased with extended incubation periods **(Tables 2** through **5).** One concern in developing the method was the possibility that the fungus would grow along the wood surface until it could penetrate more accessible surfaces outside the bolt hole, but colonization was initially greatest adjacent to the bolt hole. Fungal colonization was most rapid in untreated yellow-poplar, followed by red oak, loblolly pine, and Douglas-fir. These differences reflect the relative natural resistance of these woods to fungal attack (8). Leaching variably affected colonization on untreated control blocks. In some instances, blocks exposed for 2 weeks of leaching were colonized to a greater extent than were nonleached blocks. This was most noticeable with Douglas-fir. Leaching for an additional 2 weeks negatively affected colonization. Soluble sugars may have been lost during the prolonged leaching, making the wood less suitable for colonization.

Topically treating the test blocks dramatically decreased *Gloeophyllum trabeum* colonization in all of the species. This effect was most pronounced for pine and Douglas-fir, but was also noticeable in the hardwoods. Of the five chemicals evaluated, only copper-S-quinolinolate (Cu-8) inhibited colonization for the entire 8-week incubation period in all species.

The sodium octaborate tetrahydrate (boron) treatment provided an effective barrier for Douglas-fir and pine blocks leached no more than 2 weeks. In nonleached blocks, both penta- and copper naphthenate-treated bolt holes were colonized to varying degrees by the test fungus. Copper naphthenate has largely replaced penta as the preferred remedial treatment for protecting wood exposed when field fabrication of treated wood is necessary. Both, however, had some colonization on nonleached blocks within 4 weeks of incubation on red oak and loblolly pine. This colonization generally did not extend beyond 10 mm from the treated surface for the first 6 weeks; these treatments probably would fail eventually. Field trials with penta-treated field-drilled bolt holes have shown similar results (7).

Sodium fluoride provided the poorest protection for all species. The test fungus was isolated at all four depths from nonleached blocks of three out of four species. This chemical appeared to be effective only on Douglas-fir heartwood blocks. Heartwood was evaluated only in Douglas-fir; it is likely that the combina-

TABLE 2. – *Percent fungal colonization*[a] *in red oak as a function of weathering and incubation periods, and distance from drilled bolt holes.*

Chemical treatment	Weathering period	2 weeks 0 to 5	2 weeks 5 to 10	2 weeks 10 to 15	2 weeks 15 to 20	4 weeks 0 to 5	4 weeks 5 to 10	4 weeks 10 to 15	4 weeks 15 to 20	6 weeks 0 to 5	6 weeks 5 to 10	6 weeks 10 to 15	6 weeks 15 to 20	8 weeks 0 to 5	8 weeks 5 to 10	8 weeks 10 to 15	8 weeks 15 to 20
		Incubation period and distance from drilled bolt hole (mm)															
	(wk.)	(%)															
None[b]	0	40	8	10	0	45	33	15	18	98	85	90	90	100	100	100	100
	2	53	48	28	10	78	95	95	83	98	100	100	98	100	98	95	100
	4	0	0	0	0	40	28	38	15	98	95	83	68	100	100	100	100
Boron	0	0	0	0	0	43	8	0	0	0	0	0	0	0	0	0	0
	2	15	0	0	5	58	48	38	40	98	100	98	93	100	100	100	100
	4	65	60	60	58	100	100	100	100	100	100	100	100	100	100	100	98
	8	83	63	20	25	80	80	75	75	85	85	90	90	90	90	100	100
Cu-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Copper naphthenate	0	0	0	0	0	35	5	0	0	50	30	20	0	35	5	0	0
	2	20	0	0	0	10	0	0	0	10	0	0	0	50	50	50	10
	4	25	10	8	5	58	48	38	30	75	75	70	60	90	80	73	65
	8	0	10	0	0	30	30	30	30	60	60	55	55	90	90	100	100
NaF	0	40	10	0	0	30	20	0	0	100	100	65	50	100	100	100	90
	2	30	10	0	0	88	65	40	30	100	100	90	85	98	100	95	100
	4	55	48	35	35	75	70	60	43	100	95	85	65	83	85	85	83
	8	83	70	60	45	93	93	90	70	85	78	100	100	100	100	100	98
Penta	0	0	0	0	0	8	0	0	0	5	0	0	0	20	0	0	0
	2	0	0	0	0	20	0	0	0	40	35	5	0	45	40	5	0
	4	25	0	0	0	35	15	5	0	35	25	0	0	45	40	15	5
	8	5	0	0	0	30	25	0	0	50	40	10	10	75	60	50	40

[a] Values reflect percent recovery from 40 samples removed from treatment holes of 5 blocks.
[b] Blocks weathered for 8 weeks were lost to contamination.

TABLE 3. - *Percent fungal colonization*[a] *in yellow-poplar as a function of weathering and incubation periods, and distance from drilled bolt holes.*

Chemical treatment	Weathering period	2 weeks 0 to 5	2 weeks 5 to 10	2 weeks 10 to 15	2 weeks 15 to 20	4 weeks 0 to 5	4 weeks 5 to 10	4 weeks 10 to 15	4 weeks 15 to 20	6 weeks 0 to 5	6 weeks 5 to 10	6 weeks 10 to 15	6 weeks 15 to 20	8 weeks 0 to 5	8 weeks 5 to 10	8 weeks 10 to 15	8 weeks 15 to 20
		Incubation period and distance from drilled bolt hole (mm)															
	(wk.)	(%)															
None[b]		73	18	0	0	68	65	33	28	100	100	100	100	100	100	100	100
		83	70	60	35	65	70	75	65	93	65	75	85	100	98	98	100
		0	0	0	0	88	70	53	40	100	100	100	90	100	100	100	100
Boron		0	0	0	0	0	0	0	0	45	25	10	0	70	50	50	15
		63	40	20	0	50	48	35	38	100	95	93	93	100	100	100	100
		100	100	90	65	100	100	100	100	100	95	93	83	100	100	100	100
		78	68	50	40	78	70	60	65	65	65	75	75	95	95	90	90

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TABLE 3. — Continued from previous page.

Chemical treatment	Weathering period	Incubation period and distance from drilled bolt hole (mm)															
		2 weeks				4 weeks				6 weeks				8 weeks			
		0 to 5	5 to 10	10 to 15	15 to 20	0 to 5	5 to 10	10 to 15	15 to 20	0 to 5	5 to 10	10 to 15	15 to 20	0 to 5	5 to 10	10 to 15	15 to 20
	(wk.)	(%)															
Cu-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Copper naphthenate	0	0	0	0	0	0	0	0	0	10	0	0	0	30	0	0	0
	2	0	0	0	0	10	0	0	0	10	0	0	0	18	10	0	0
	4	30	20	10	0	65	55	43	25	93	78	70	58	100	100	100	98
	8	20	10	0	0	50	50	25	20	50	55	30	35	80	80	70	70
NaF	0	40	10	0	0	100	90	65	40	100	100	95	75	100	100	95	70
	2	70	48	40	23	98	90	78	58	100	100	95	85	90	90	90	85
	4	78	65	55	43	85	78	70	55	100	98	93	85	95	90	90	90
	8	100	70	55	20	90	90	75	78	90	73	58	40	100	100	100	98
Penta	0	0	0	0	0	0	0	0	0	25	15	0	0	10	0	0	0
	2	0	0	0	0	15	5	0	0	40	30	25	10	45	40	20	20
	4	15	5	0	0	28	10	0	0	35	25	0	0	60	60	50	40
	8	18	0	0	0	50	40	25	13	65	65	35	30	95	85	83	80

[a] Values reflect percent recovery from 40 samples removed from treatment holes of 5 blocks.
[b] Blocks weathered for 8 weeks were lost to contamination.

TABLE 4. — Percent fungal colonization[a] in loblolly pine as a function of weathering and incubation periods, and distance from drilled bolt holes.

Chemical treatment	Weathering period	Incubation period and distance from drilled bolt hole (mm)															
		2 weeks				4 weeks				6 weeks				8 weeks			
		0 to 5	5 to 10	10 to 15	15 to 20	0 to 5	5 to 10	10 to 15	15 to 20	0 to 5	5 to 10	10 to 15	15 to 20	0 to 5	5 to 10	10 to 15	15 to 20
	(wk.)	(%)															
None[b]	0	13	10	10	0	0	0	0	0	90	88	88	75	80	80	75	70
	2	20	25	25	20	15	10	5	8	65	60	60	53	83	85	73	73
	4	0	0	0	0	0	0	0	0	68	43	45	30	100	83	60	55
Boron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	100	100	83	70	100	100	100	100	100	100	100	88	100	100	100	100
	8	93	10	65	55	88	93	98	85	85	85	90	90	75	75	100	100
Cu-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Copper naphthenate	0	10	0	0	0	15	0	0	0	15	0	0	0	15	0	0	0
	2	40	0	0	0	15	0	0	0	10	0	0	0	20	15	0	0
	4	45	25	3	0	90	80	65	50	93	90	90	70	100	100	100	90
	8	15	5	0	0	55	55	50	50	50	50	50	50	80	80	80	80

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TABLE 4. - Continued from previous page.

Chemical treatment	Weathering period	Incubation period and distance from drilled bolt hole (mm)															
		2 weeks				4 weeks				6 weeks				8 weeks			
		0 to 5	5 to 10	10 to 15	15 to 20	0 to 5	5 to 10	10 to 15	15 to 20	0 to 5	5 to 10	10 to 15	15 to 20	0 to 5	5 to 10	10 to 15	15 to 20
	(wk.)	(%)															
NaF	0	0	0	0	0	0	0	0	0	30	10	0	0	50	50	20	20
	2	90	70	55	53	98	90	83	80	100	100	90	95	100	100	100	93
	4	98	95	90	80	100	100	100	88	100	100	95	90	100	100	100	100
	8	100	85	68	60	100	98	88	83	95	95	95	100	100	100	100	100
Penta	0	10	0	0	0	8	0	0	0	15	10	0	0	10	0	0	0
	2	0	0	0	0	15	0	0	0	35	25	10	5	45	35	5	0
	4	20	5	0	0	10	5	0	0	30	10	0	0	40	30	15	15
	8	10	0	0	0	40	35	0	0	50	50	20	5	60	50	48	25

[a] Values reflect percent recovery from 40 samples removed from treatment holes of 5 blocks.
[b] Blocks weathered for 8 weeks were lost to contamination.

TABLE 5. - Percent fungal colonization[a] in Douglas-fir as a function of weathering and incubation periods, and distance from drilled bolt holes.

Chemical treatment	Weathering period	Incubation period and distance from drilled bolt hole (mm)															
		2 weeks				4 weeks				6 weeks				8 weeks			
		0 to 5	5 to 10	10 to 15	15 to 20	0 to 5	5 to 10	10 to 15	15 to 20	0 to 5	5 to 10	10 to 15	15 to 20	0 to 5	5 to 10	10 to 15	15 to 20
	(wk.)	(%)															
None[b]	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	18	10	5	0	78	70	80	60	73	65	55	50
	4	0	0	0	0	0	0	0	0	73	60	55	35	95	83	55	50
Boron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	100	98	70	55
	4	83	60	50	45	40	50	40	35	50	50	40	10	50	50	45	20
	8	20	10	0	0	45	30	25	20	45	35	35	18	65	60	55	60
Cu-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Copper naphthenate	0	10	0	0	0	0	0	0	0	30	0	0	0	50	10	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	10	5	0	0
	4	5	0	0	0	10	0	0	0	33	28	10	10	43	25	5	3
	8	0	0	0	0	20	20	5	0	30	20	15	10	50	50	65	50
NaF	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	5	0	0	0	30	30	20	5	80	70	60	45
	4	20	15	5	3	28	25	15	5	85	80	60	45	80	75	50	50
	8	8	0	0	0	43	20	10	5	28	13	8	5	45	40	5	0
Penta	0	0	0	0	0	0	0	0	0	5	0	0	0	10	0	0	0
	2	0	0	0	0	0	0	0	0	25	15	10	8	35	20	5	0
	4	5	0	0	0	5	0	0	0	15	5	0	0	30	20	0	0
	8	0	0	0	0	13	0	0	0	35	13	0	0	35	20	3	0

[a] Values reflect percent recovery from 40 samples removed from treatment holes of 5 blocks.
[b] Blocks weathered for 8 weeks were lost to contamination.

tion of the moderately durable heartwood and sodium fluoride provided enhanced protection.

Leaching was extemely detrimental to the protective chemical effects. As expected, water-soluble chemicals were far more sensitive to leaching exposure. Boron-treated red oak and yellow-poplar blocks that were leached for 2 weeks were rapidly colonized. Boron appeared to leach more slowly from the two conifers. Colonization was not evident in boron-treated pine blocks leached for 2 weeks, whereas similarly treated Douglas-fir was colonized only after 8 weeks of incubation. After 2 more weeks, the value of topical treatment was largely negated in all four species.

The sensitivity of boron-based biocides to leaching loss is well documented (4) and is confirmed by our results with these small blocks. The significance of leaching on a bolt hole is difficult to determine. A fastener is typically driven into a slightly under-sized hole so that the amount of moisture moving along the fastener and into the untreated wood exposed during fabrication may be negligible. Newbill and Morrell (7) showed that boron sprays protected field-drilled bolt holes in Douglas-fir poles exposed for over 10 years in western Oregon. Thus, the bolt hole environment may be less susceptible to leaching.

Leaching of bolt holes treated with sodium fluoride also lowered the resistance to fungal colonization, regardless of the wood species. As with boron, leaching of fluoride from pine and Douglas-fir was initially slower than from either hardwood. Douglas-fir appeared to be somewhat more resistant to colonization after leaching, evidence of some residual fluoride.

All three oilborne formulations were less sensitive to leaching exposure. Cu-8 was by far the most leach-resistant chemical. This was demonstrated by the absence of the test fungus from all blocks regardless of the length of either the leaching or the incubation periods. Leaching of blocks treated with copper naphthenate-treated resulted in higher levels of fungal colonization as leaching time or incubation increased. Fungal colonization was greatest in copper naphthenate-treated pine leached for 4 weeks and incubated for 6 weeks. The two hardwood species had lower but similar levels of colonization. Again, Douglas-fir was somewhat more resistant to colonization even after the extended leaching period.

Penta performance was similar to that of copper naphthenate, showing increasing degrees of colonization with prolonged leaching and incubation. Morrell et al. (5) found that neither penta nor copper naphthenate migrated more than 10 mm from a highly concentrated paste into Douglas-fir sapwood. Relatively small amounts of concentrated biocide are applied to the wood surface in bolt-hole treatments. Therefore, little chemical is available to diffuse more deeply into the wood. This is particularly critical when oilborne materials are unable to migrate farther as splits or checks develop. Water-soluble treatments can move along developing checks or splits so that newly exposed wood is less susceptible to fungal attack.

Although Cu-8 is an excellent fungicide, its enhanced performance compared with copper naphthenate or penta was unexpected. This may reflect the excellent biocidal properties of both the copper and quinoline components. Naphthenic acid lacks the biocidal properties of quinoline (3), and *G. trabeum* is tolerant to pentachlorophenol (10). However, biocidal efficacy does not completely explain the better performance of Cu-8. Clearly, this chemical also resisted leaching to a greater extent than did either penta or copper naphthenate.

Conclusions

In drier climates or in situations where tight-fitting fasteners are used, boron or Cu-8 provide the best protection against fungal colonization. Where the leaching risk is higher, Cu-8 is clearly more effective than the other four chemicals we evaluated. Treatments were most effective in Douglas-fir heartwood, followed by loblolly pine. Protection was generally lower for red oak and yellow-poplar. Field fabrication of bridges constructed from these hardwood species may pose special challenges in decay prevention.

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