LABORATORY IMMERSION METHOD FOR ACCELERATED PREDICTION OF PRESERVATIVE LEACHING FROM TREATED WOOD EXPOSED TO PRECIPITATION[1]

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Abstract. This article reports on the development of accelerated laboratory methods to allow estimation of preservative leaching from pressure-treated wood exposed to precipitation. End-matched lumber specimens were pressure-treated with a boron–copper formulation and exposed to natural weathering for 1 yr, laboratory immersion protocols, or a laboratory-simulated rainfall protocol. The rainfall runoff or immersion water was collected at intervals according to the method used and analyzed for concentrations of copper and boron. Of the laboratory methods evaluated, the simulated rainfall approach resulted in leaching patterns most similar to outdoor exposure, especially in the case of copper. However, this method is relatively complex and not ideally suited for standardized use. Although the immersion methods evaluated initially exaggerated leaching, reasonable approximations of leaching from 1 yr of natural weathering were achieved with accelerated testing. Models were developed to relate hours of immersion to millimeters of precipitation, and used to evaluate how well the immersion methods might predict leaching from natural weathering over many years of exposure. One of the methods produced boron and copper leaching estimates that were within 15% and 7%, respectively, of losses predicted for wood exposed to 5 yr of natural weathering. The results indicate that laboratory immersion methods have value in estimating long-term preservative leaching from treated wood products exposed to precipitation.

Keywords: Wood preservative, leaching, precipitation, accelerated test methods, immersion.

INTRODUCTION

Biocides and other constituents used to improve the durability and performance of wood exposed outdoors are subject to leaching from precipitation, standing water, or soil moisture. Evaluating resistance to leaching is a critical step in determining whether a test formulation is likely to provide long-term protection. Similarly, quantifying the expected release of biocide from treated wood into the environment is a key component of evaluating a test formulation's potential for environmental impacts. Thus, durability concerns are focused on the quantity of biocide remaining in the wood, whereas environmental concerns are focused on the quantity of biocide lost from the wood. This distinction has had practical consequences for the manner in which leaching is evaluated. Conventional standard leaching tests were developed to address durability concerns and designed to greatly accelerate leaching. Although these tests are valuable for ensuring long-term

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durability, they are less useful for evaluating potential environmental impacts.

The methods used to evaluate preservative leaching are discussed in Lebow (2014) and Lebow et al (2008, 2017) and will be only briefly summarized here. In North America, the most commonly used standardized leaching method for preservative-treated wood is American Wood Protection Association (AWPA) Method E11-16, Standard Method for Accelerated Evaluation of Preservative Leaching (AWPA 2017). This method uses small (19 mm) blocks immersed for 14-17 d. Other countries also use immersion of relatively small specimens when evaluating new preservatives for resistance to leaching (BSI 1997; CNS 2000; JSA 2004). In each case, the method is intended to greatly accelerate leaching in an effort to evaluate the potential for long-term protection.

Developing accelerated methods to provide reasonable estimates of environmental releases from in-service products has proven challenging, especially for most treated wood that is subject to leaching from precipitation. In one such effort, the Organization for Economic Cooperation and Development (OECD) describes an approach involving a brief dip immersion using small (15 by 25 by 50–mm) specimens (OECD 2009). The dip immersions can be either three 1-min dips, two 1-h dips, or one 2-h dip per day for 19 d. Although intended to simulate in-service leaching, there is some concern that relatively short immersions approach may not represent commercially produced lumber (Baines 2005) or not produce the moisture conditions reported for wood products exposed to natural weathering (Lebow et al 2008; Bahmani et al 2016). One study which compared outdoor leaching with the OECD method concluded that the laboratory method risked underestimating in-service leaching (Morsing and Lindegaard 2004), whereas another reported that the OECD method resulted in less leaching than other laboratory methods (Lesar et al 2008). Longer immersion times may allow greater wetting of specimens, although specimen dimensions must be considered. A recent study noted that although the leaching from the small blocks used in the AWPA standard method was unrealistically high, employing the same method with larger lumber specimens appeared to underestimate copper losses when compared with leaching observed in an outdoor exposure (Lebow et al 2017). These findings indicate that there is potential for the use of immersion periods to simulate leaching from precipitation if a suitable combination of immersion period–specimen size can be identified.

Another approach to evaluating leaching from wood exposed to precipitation is simulated rainfall (Cooper and MacVicar 1995; Lebow et al 2003; Lebow et al 2004; Morrell et al 2004; Mitsuhashi et al 2007; Mankowski and Manning 2008; Lebow et al 2017). Simulated rainfall can create more realistic wetting conditions and allows some control over rainfall rates and frequency. Lebow et al (2017) reported that lumber specimens exposed to simulated rainfall produced a pattern and quantity of leaching most similar to that of natural exposure, especially for copper. However, the equipment required to simulate rainfall is more complex than that required for other laboratory leaching methods, and none of these approaches have been standardized.

Ideally, a standard method would be relatively simple to describe and conduct, while still providing meaningful results. In addition, the specimen dimensions (surface area to volume ratio) would more closely relate to dimension lumber so that the release rates could be applied to in-service commodities. Recent research indicated that there is potential for using immersion of lumber-sized specimens to simulate aboveground leaching if the immersion periods can be adjusted to simulate moisture contents observed in wood products exposed outdoors. In this article, we evaluated extended laboratory immersion leaching methods for their ability to simulate moisture contents and leaching rates similar to that from wood exposed to natural precipitation. The results were compared with leaching from outdoor exposure tests and with those of other accelerated tests reported in Lebow et al (2017).

MATERIALS AND METHODS

The specimens leached in this study were end-matched and pressure-treated in the same charge as those evaluated in an earlier study (Lebow et al 2017). Specimens were prepared from five southern pine parent boards with dimensions of 38 by 92 by 2438 mm (2 by 4 by 8 ft., nominal). Specimens were selected to be free of heartwood, knots, and other visible wood defects. Eight matching 38 by 92 by 102-mm-long lumber sections were cut from each parent board (only six of these specimens were used in the current study). One specimen cut from each board was randomly assigned to one of the six leaching conditions (described in the following) so that each leaching condition had one replicate from each parent board. All specimens were conditioned to constant weight and approximately 10% MC at 23°C and 55% RH before preservative treatment. The lumber specimens were end-sealed with two coats of a neoprene rubber sealant to prevent end-grain penetration during preservative treatment and subsequent leaching from the end-grain.

Preservative Treatment Process

The preservative evaluated in this study was an alkaline borax–copper formulation containing 1.3% elemental boron and 0.5% elemental copper. This formulation was selected because it contains a readily leachable component (boron) and a less leachable component (copper). It is important to note that this formulation is not currently used for commercial pressure treatments and that the quantities of preservative leached reported in this study are not directly applicable to any current commercial pressure treatment preservatives. A full cell treatment schedule was used to enhance uniformity of treatment. An initial 30-min vacuum at −81 kPa (gauge) was followed by introduction of the treatment solution and a 60-min pressure period at 1034 kPa (gauge). The specimens were weighed before and after treatment to allow the calculation of preservative uptake. Because end-matched specimens were used and because all specimens were treated in a single charge, retentions were similar between treatment groups (Table 1). Following treatment, the specimens were stored in plastic bags for 1 wk to prevent rapid drying and then reequilibrated in a room maintained at 23°C and 55% RH.

Leaching Conditions Evaluated

For this study, the research described in Lebow et al (2017) was expanded by conducting an additional trial of outdoor leaching under natural exposure along with two laboratory immersion approaches. For comparison, this article also presents data from earlier research with a simulated rainfall method and a method similar to the existing AWPA Standard E11 (AWPA 2017). The leaching methods are summarized in Table 1. The laboratory methods were conducted at room temperature, whereas the temperature of the outdoor specimens varied with weather conditions.

E11Immerse (modification of AWPA Standard E11). This laboratory immersion method is patterned after AWPA Standard E11-16, Standard Method for Accelerated Evaluation of Preservative Leaching (AWPA 2017). AWPA Standard E11 is currently the most commonly used standardized leaching method in North America but uses small 19-mm blocks and is intended to greatly accelerate leaching. In this study, single 38 by 92 by 102-mm lumber specimens were used instead of multiple smaller blocks. The end-grain of the specimens had also been sealed with a neoprene rubber coating to limit leaching to the radial and tangential surfaces. A larger leaching container was used, and the volume of leaching water was increased to 600 mL in proportion to the increased surface area. As prescribed in the method, the specimens were vacuum impregnated with deionized water before immersion (also in deionized water). They were immersed for a total of 16 d, with water collections at 0.25, 1, 2, 4, 7, 9, 11, 14, and 16 d (Table 1).

100hrImmerse (each immersion period 100 h). The Lebow et al (2017) research indicated that the E11Immerse method resulted in less copper leaching than was observed for specimens exposed outdoors. It was hypothesized

Table 1. Leaching methods employed, and initial boron and copper content in specimens based on uptake during pressure treatment.

		Treatment uptake (g)			
		Boron		Copper	
Designation	Leaching method	Mean	Stdev	Mean	Stdev
E11Immerse	Vacuum impregnated and immersed according to American Wood Protection Association E11 with nine water collections at 0.25, 1, 2, 4, 7, 9, 11, 14, and 16 d	2.90	0.29	1.11	0.11
100hrImmerse[a]	Immersed with nine water collections at 100-h intervals (4.2, 8.3, 12.6, 17, 21.2, 25.3, 29.6, 34.0, and 37.9 d)	2.87	0.30	1.11	0.12
7dayImmerse[a]	Immersed with nine water collections at weekly intervals (7, 14, 21, 28, 35, 42, 49, 56, and 63 d)	2.90	0.30	1.12	0.11
SimRain	Simulated rainfall with water collections at 2, 4, 9, 11, 16, 18, 23, and 25 d	2.90	0.29	1.12	0.11
Outdoor1	Outdoor year 1, natural rainfall with eight water collections at 39, 67, 103, 116, 151, 182, 224, and 268 d (based on rainfall received)	2.98	0.24	1.15	0.09
Outdoor2	Outdoor year 2, natural rainfall with eight water collections at 41, 79, 97, 114, 164, 186, 207, and 250 d (based on rainfall received)	2.89	0.29	1.11	0.11

[a] Each immersion period was 100 h or 7 d for these methods, respectively.

that this was a result of the shorter leaching duration, which may have limited the amount of soluble copper that had time to diffuse to the surface from the interior of the specimens. In this version, the method was similar to E11Immerse except that the immersion periods between water collections were extended to approximately 100 h to allow more time for diffusion to occur. In addition, the specimens were not initially impregnated with water to more closely simulate the more gradual wetting that occurs in natural exposures. Although water collections were targeted for 100-h intervals, allowances were made for worker convenience, and some intervals were slightly more than or less than 100 h (Table 1). The total immersion time using this method was 910 h or 37.9 d.

7dayImmerse (each immersion period 7 d). This method was identical to that of the 100hImmerse, except that the collection intervals were extended to 7 d. Again, the intent of the longer interval is to allow more time for solubilized copper to diffuse from the interior to the exterior of the blocks. In this case, the total immersion time is approximately four times greater than that of the AWPA E11 method. The total immersion time using this method was 63 d.

SimRain (simulated rainfall). This method used simulated rainfall to leach specimens, which were placed separately into stainless steel trays that were slightly wider and longer (98 by 108 mm) than the specimens. The specimens were supported on a plastic grid so that they were above the tray outlet drain. Runoff from the specimens drained through the tubing into polyethylene collection containers below. Simulated rainfall (RO water) was applied from a rotating fan-spray nozzle mounted 1 m above the specimens. The rate of rainfall was controlled at 8 mm/h by the speed of the nozzle sweep and by cycling the nozzle off and on during rainfall events. Daily rainfall was applied at 60-min intervals (60 min on, 60 min off) over 13 h (a total of 7 h of rainfall per day). Rainfall was applied 4 d per week (Monday-Thursday). The runoff from the specimens was collected twice per week, after 112 mm of rainfall had accumulated. This pattern was repeated for 4 wk, yielding a total of 896 mm of rainfall and eight leachate collections.

Outdoor1 (exposure to natural precipitation). This method assessed leaching under natural exposure conditions. The lumber specimens were placed into stainless steel trays in the manner similar to the SimRain method and exposed outdoors from

March 6 to November 29, 2014, at a site near Madison, WI. A weather station installed adjacent to the specimens collected rainfall data at 15-min intervals. The specimens were exposed to 868 mm of rainfall, and the leachate was collected eight times, after rainfall accumulations of 113, 105, 114, 121, 174, 102, 92, and 45 mm. The intent was to collect rainfall after approximately 112 mm of accumulation, corresponding to the collection intervals used in the simulated rainfall methodology. However, the final leaching period was curtailed because of sustained subfreezing temperatures.

Outdoor2 (exposure to natural precipitation). This trial was similar to Outdoor1, but in this case the specimens were exposed from March 6 to November 11, 2015. The specimens were exposed to a total of 835 mm of rainfall, and the leachate was collected eight times after rainfall accumulations of 99, 100, 114, 102, 103, 104, 118, and 96 mm.

MC Measurements

A resistance-type moisture meter was used to evaluate the internal MC of Outdoor1 and Outdoor2 specimens. Because electrical resistance drops rapidly when free water is present in cell lumens, resistance-type moisture meters lose accuracy when the wood MC exceeds the FSP (approximately 26-28%). However, some change in resistivity does occur at higher moisture contents, and researchers have recently presented data indicating that measurements greater than 30% MC can be at least semiquantitative if the electrodes are glued or screwed into the wood (Brischke and Lampen 2014; Lebow and Lebow 2016). The moisture meter used in this study was a General Electric Protimeter Timbermaster (General Electric Sensing, Danbury, CT), which displays MC readings between 7% and 100%. The internal calibration recommended for southern pine was used in this study. Stainless steel screws were used as electrodes because preliminary trials indicated that the pin electrodes tended to yield lower, and more variable, MC readings. Initially, 10-mm diameter holes were drilled to a depth of 19 mm into the center of a narrow face of each specimen and filled with silicone sealant. After the sealant dried, trim head wood screws (#7, 76 mm length) were driven through the sealant and into the specimen until they extended to within 19 mm of the opposite narrow face. Pilot holes were used to ensure that the screws remained aligned as they were driven into the wood. The two screws, spaced 25 mm apart, were thus measuring the MC in an internal zone that was approximately 39 mm from each end and 19 mm from the wide and narrow faces of the specimens (Fig 1).

The copper hydroxide and borax retention in the specimens was relatively high, and preliminary trials indicated than an adjustment was needed to correct the resistance readings. The adjustment was developed using a method previously described in Lebow and Lebow (2016). In brief, thin strips (3 mm thick by 10 mm wide by 47 mm long) of southern pine sapwood were vacuum-impregnated with preservative and then spread on a drying rack under ambient laboratory conditions. After 1, 2, 3, 4, or 5 h of air drying, preselected sets of specimens were removed from the drying rack and individually wrapped in plastic film to prevent further drying. After 72 h, the specimens were unwrapped, weighed, and their resistance MC recorded. The specimens were then oven-dried at 104°C to allow determination

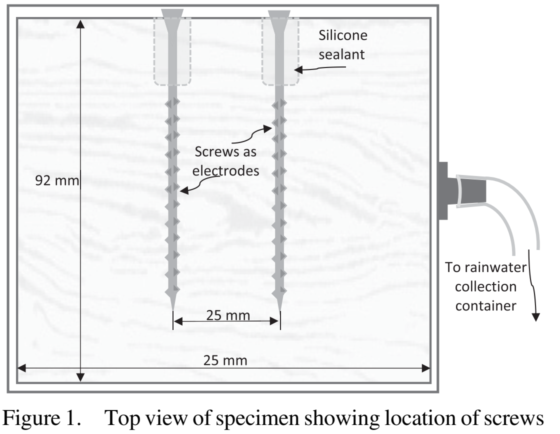

Figure 1. Top view of specimen showing location of screws used as electrodes. Depicts specimens set up for outdoor rainwater collection.

of gravimetric MC. Matched specimens treated with deionized water were included for comparison. The data were used to develop a segmented linear regression model, with censoring and heterogeneity between segments. The MC readings reported in this article have been adjusted according to this model. This procedure also indicated that adjusted moisture meter readings greater than 40% were poorly correlated to gravimetric oven-dry MC.

Temperature may also affect resistance readings, and a temperature correction was developed for the outdoor specimens. In this case, the leaching specimens were used to develop the correction. The specimens were wrapped in plastic to prevent drying and equilibrated at set temperatures ranging from 4 to 31°C. The readings were then adjusted to those obtained at 20°C.

Analysis of Leachate Solutions

The collected leachate was acidified to less than pH 2 with nitric acid to maintain copper solubility and analyzed by inductively coupled plasma emission spectrometry (Horiba Instruments, Ultima II, Edison, NJ).

Statistical Methods and Analysis

Cumulative leaching was modeled using nonlinear mixed effect models (Pinheiro and Bates 2000) with the nlme package (version 3.1-128, Pinheiro et al 2016) in the statistical package R (version 3.3.1, R Core Team 2016). The nonlinear relationships assumed were asymptotic regressions with offsets. The expected cumulative leached amount was modeled mathematically with a general form:

$$y = \beta_1(1 - \exp(-\beta_2(x - \beta_3))),$$

where

y = cumulative leached amount,
x = cumulative rain (mm) or time exposure (h),
β_1 = asymptote,
β_2 = rate constant, and
β_3 = offset (value of x at $y = 0$, which implies either an initial pulse or an initial delayed release).

However, the models also included random effects and dependencies to capture the within-specimen dependencies over exposure periods and the within–parent board dependencies across the different treatment conditions; these were associated with the asymptote and rate constant parameters. Boron leaching was fit with one model, with separate parameter estimates for the asymptotes, rate constants, and offsets for each of the leaching conditions. Copper leaching was fit to a similar model. Long-term extrapolations for prediction of leaching were based on hypothetical exposures to 500, 1000, 2000, and 5000 mm of rain or hours of exposure, depending on the leaching condition. Population prediction intervals were derived using simulation as described in Bolker (2008). Extrapolations were made from equations using parameters generated from random samples ($n = 1000$) from multivariate normal distributions based on the parameter and variance–covariance matrix estimates of the statistical models. The 95th lower prediction interval is given as the 0.025 quantile of the extrapolations and the 95th upper prediction interval is the 0.975 quantile of the extrapolations. These intervals include within-exposure condition variation but not between-exposure condition variation.

RESULTS AND DISCUSSION

In this study, the outdoor leaching trials were intended to serve as the benchmark of actual leaching under "real-world" conditions. For treated wood exposed aboveground, leaching is a function of amount of precipitation and the resulting wood MC. The pattern of rainfall and internal MC of the specimens for two separate 1-yr exposures are shown in Fig 2. The pattern of moisture gain and loss in the specimens was fairly similar each year, although the specimens gained moisture most rapidly in year 1. In both years, specimens dried somewhat during some parts of the summer, before regaining moisture and remaining consistently wet throughout the fall. Less drying between rainfall events may have occurred in the fall because of lower temperatures and less direct sun exposure. The sustained fall moisture contents (Fig 2) may have facilitated migration of solubilized boron and copper to the wood surface, resulting in an increase in the amount of leaching per unit rainfall. In general, the two separate years of outdoor leaching resulted in remarkably similar quantities and patterns of leaching (Figs 3 and 4), which provides some confidence in the use of these values as the benchmark for comparison with laboratory methods.

The manner in which leaching results are calculated and expressed can substantially affect interpretation of the data. The quantity leached can be calculated as a percentage of the original preservative retention or on the basis of the amount of preservative released per unit surface area.

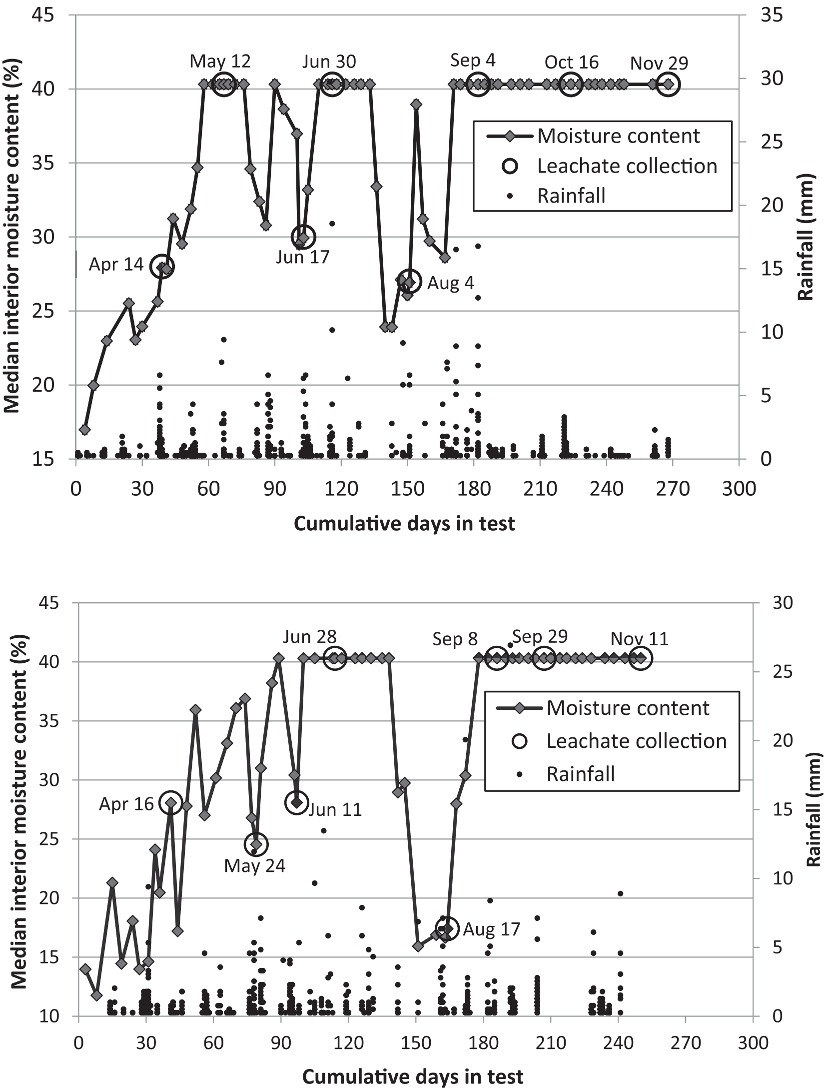

Figure 2. Rainfall and median interior MC for specimens exposed outdoors for year 1 (top) or year 2 (bottom). MC is capped at 40% because of method limitations. Individual markers show rainfall amounts in 15-min intervals.

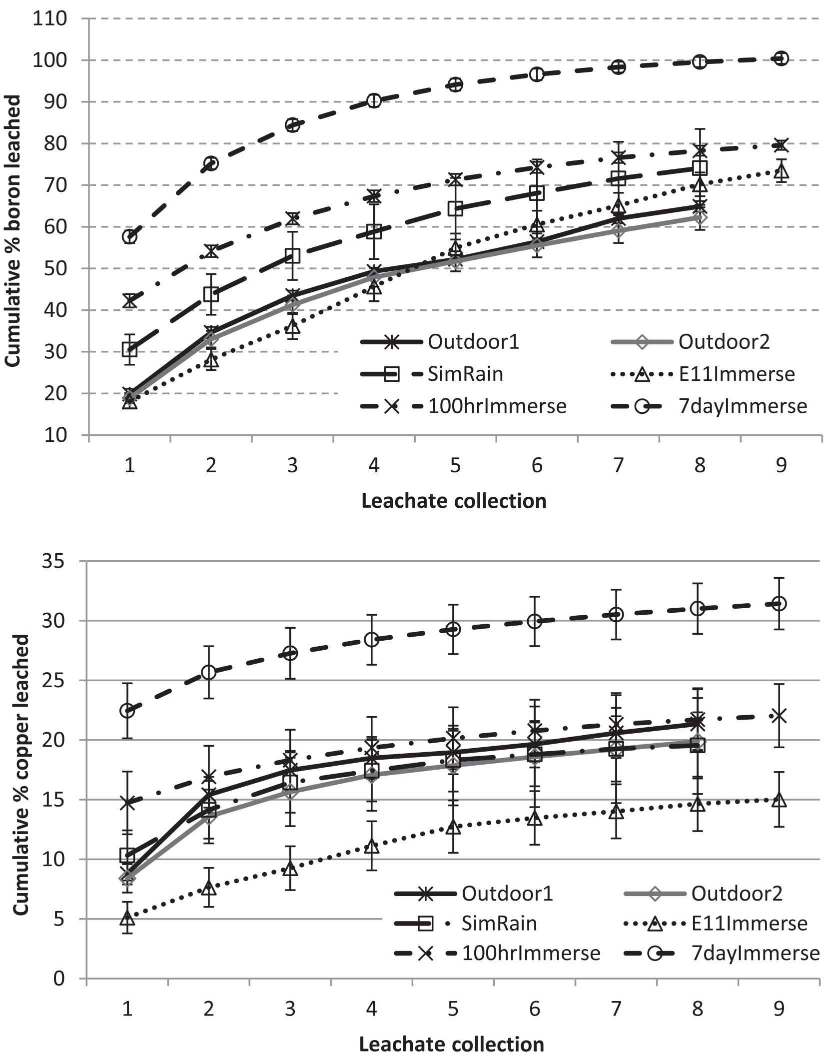

Figure 3. Cumulative percent of boron (top) or copper (bottom) leached by leaching interval. Error bars show 1 standard deviation from the mean.

Calculation of leaching as a percentage of the original preservative retention is easily understood, accounts for differences in initial loadings, and provides an indication of the quantity of preservative remaining for future leaching or for efficacy against wood-degrading organisms. However, the amount of preservative released per unit surface area may be more applicable when attempting to estimate environmental releases from a treated wood structure. In addition, the quantity leached can be expressed as a function of leaching interval, leaching time, or amount of precipitation. In this article, we report and discuss the results in several ways to allow a better understanding of how the accelerated methods compare with leaching under natural conditions. The primary objective of this research was to develop an accelerated laboratory method that can be used to estimate leaching per unit surface area as a function of amount of precipitation.

When expressed as cumulative percentage leached over exposure periods, the specimens immersed

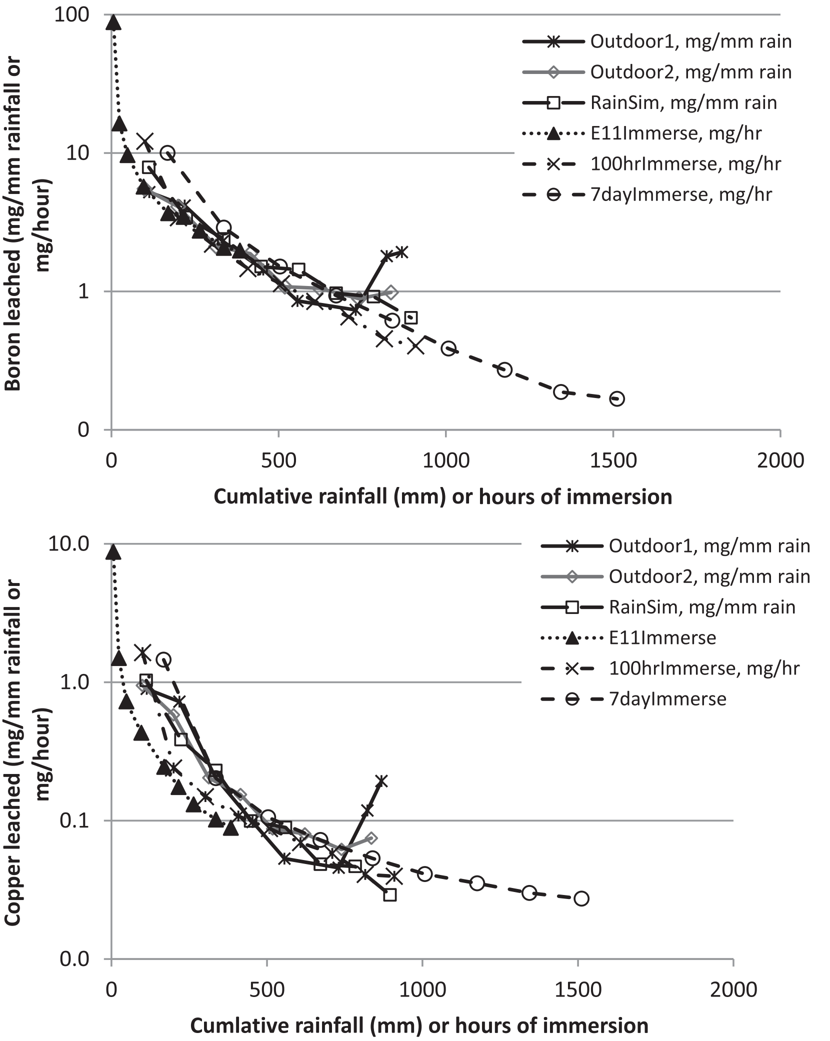

Figure 4. Leaching as a function of amount of rainfall or hours of immersion for boron (top) and copper (bottom).

for weekly intervals (7dayImmerse) had the greatest leaching, followed by the specimens immersed for 100-h intervals (Fig 3). Lumber specimens leached using the AWPA E11 method (AWPA 2017) had the least leaching of the accelerated methods, particularly in the case of copper.

Because copper is the primary active agent in the most common types of treated wood, it is important that the leaching method does not greatly underestimate copper losses. It is worth noting that calculating leaching solely by leaching interval obscures the large differences in duration of leaching. In this study, the E11 method had the shortest intervals between water collections, whereas the outdoor exposures had the longest intervals. On the basis of percent leached per day, the E11 method had the greatest copper leaching. However, assuming that time is required for solubilized copper to move from the interior of the specimens to the surface, the relatively low total percentage of copper leaching from the E11 method is likely a result of shorter exposure time. This observation during the earlier study (Lebow et al 2017) led to the decision to evaluate more lengthy immersion periods in the current research.

Because the objective of this study was to develop a laboratory leaching method that more closely simulated actual leaching outdoors, it was necessary to be able to relate the results of the laboratory methods to quantity of precipitation. Although this was readily accomplished with the simulated rainfall method, relating the immersion methods required finding a relationship between time of immersion and volume of precipitation. In Fig 4, leaching is expressed as quantity (mg) leached either per hour (immersed specimens) or per millimeter rainfall (outdoor and simulated rainfall specimens) to allow comparison. Note that in this case, because all specimens had the same dimensions, there is no need to compare leaching on the basis of surface area.

When expressed on a per hour basis, releases from the E11Immerse specimens are initially very high because of the short intervals between water collections and because they were initially impregnated with water (Fig 4). As the leaching continued, the more leachable components near the surface were depleted and a rapid decrease in leaching was observed for the E11Immerse specimens, especially in regard to copper. Although the pattern and quantity of leaching observed with the E11Immerse specimens do not correspond well to those observed in outdoor leaching, the results obtained with the 100hrImmerse, and to some extent 7dayImmerse, methods are more promising. The 100hrImmerse method also initially caused boron and copper losses greater than that observed outdoors but more closely mimicked outdoor leaching as the exposure continued. As shown in the leaching data in Fig 5, leaching of copper from the 100hrImmerse specimens relates surprisingly well to that of the outdoor specimens assuming that 1 h of immersion is equivalent to 1 mm of rainfall. Leaching of boron from the 100hrImmerse specimens is greater than that observed for outdoor specimens, but this difference is primarily associated with the initial leaching period. In subsequent leaching intervals, 1 h of immersion relates well to 1 mm of rainfall (Figs 4 and 5). The greater release observed during the first interval with the immersion method is likely a result of more rapid initial wetting. The median interior MC of the outdoor specimens remained less than 30% during the first interval (Fig 2), and this may have limited the diffusion of copper and boron from the interior of the specimens to the surface.

The reason that the use of the 100-h immersion intervals caused 1 h of immersion to be approximately equal to 1 mm of rainfall for copper leaching is unclear. The relationship may simply be coincidental. However, it does provide a convenient way to relate the accelerated immersion testing to typical volume of rainfall at a specific location. Having this relationship is necessary to relate leaching by immersion to leaching from precipitation. Further analysis is underway to better understand and characterize this relationship. By assuming that 1 h of immersion is equivalent to 1 mm of rainfall for the 7dayImmerse, E11Immerse, and 100hrImmerse methods, the observed leaching was modeled to evaluate how well the accelerated leaching methods might predict the amount of boron and copper released during more prolonged in-service exposures. Leaching for specimens exposed outdoors for 1 yr were also modeled to estimate leaching over longer exposures, and these estimates were compared with those of the laboratory methods. Parameter estimates for the models are shown in Table 2. Using these models, Table 3 shows how well the laboratory methods estimated outdoor leaching when extrapolated over 0.5, 1, 2, and 5 yr of exposure, assuming a hypothetical location receives 1000 mm of precipitation per year. As expected, predicted leaching with the SimRain method most closely matched that of outdoor leaching for both boron and copper. However, the 100hrImmerse method also performed reasonably well in predicting leaching, especially over the longer term. It initially overpredicts leaching because of the greater initial release (approximately three times as much at 50 mm of rainfall, and 1.7 times as much at 100 mm of rainfall) but stays within about 7-15% of the outdoor methods for longer exposures. The 100hrImmerse method did particularly well in predicting the long-term release of copper, which

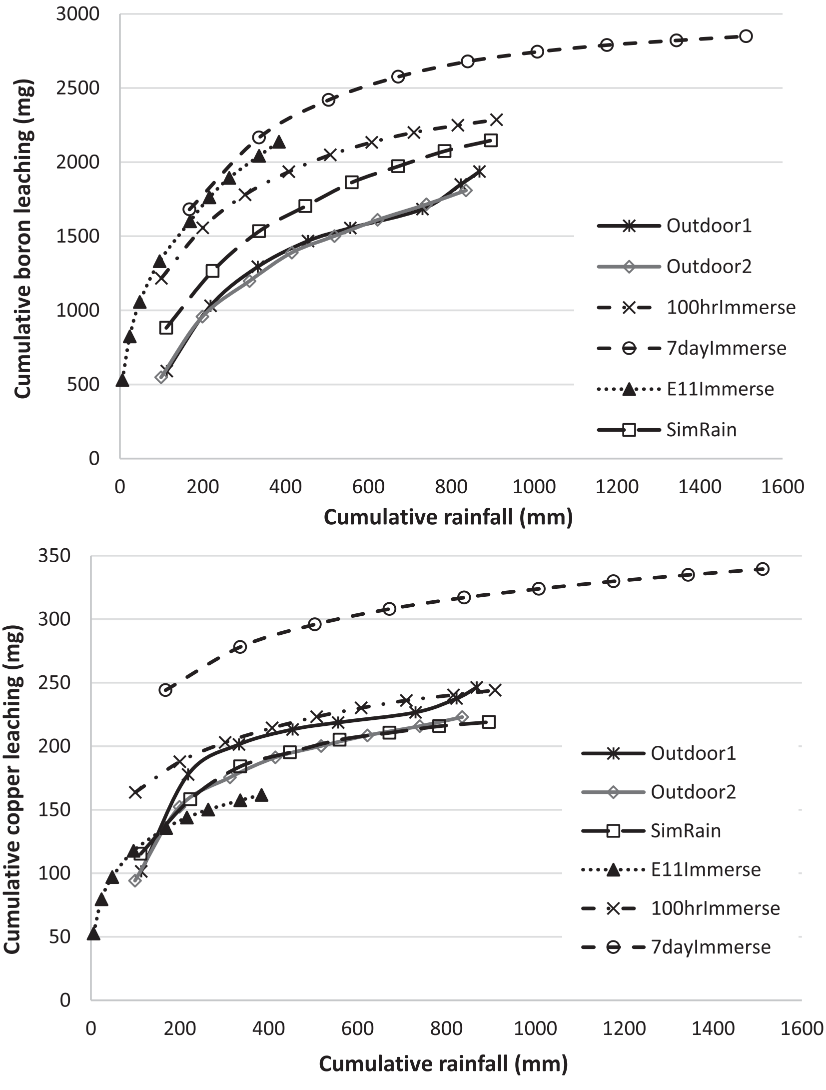

Figure 5. Comparison of laboratory leaching methods to outdoor exposure, assuming 1 h of immersion = 1 mm of rainfall.

is commonly used in exterior use wood preservatives and may be more representative than boron for leaching from exterior wood preservatives. By contrast, the E11Immerse method performed fairly well in predicting long-term boron leaching but substantially underestimated long-term copper loss. As a result of the very high leaching observed during the first week of immersion, the 7dayImmerse method overestimated long-term depletion of both boron and copper, even after 5 yr of rainfall.

Of the laboratory methods evaluated, the simulated rainfall approach resulted in leaching patterns most similar to outdoor exposure, especially in the case of copper. However, an immersion method would be more practical if duration of immersion can be related to amount of rainfall. The results of this study do indicate that relatively simple immersion methods using lumber-size specimens have the potential to provide reasonable estimates of long-term leaching from treated wood exposed to precipitation. The key to this

Table 2. Model parameter estimates.

Leaching method	Asymptote (mg), $\hat{\beta}_1$	Rate constant (h^{-1} or mm^{-1}), $\hat{\beta}_2$	Offset (h or mm), $\hat{\beta}_3$
Boron leaching model			
7dayImmerse	2924 (134.5)	0.0028 (0.00019)	−132.9 (13.46)
100hrImmerse	2357 (135.8)	0.0033 (0.00025)	−125.4 (12.96)
Outdoor1	2057 (138.5)	0.0026 (0.00021)	−26.4 (8.96)
Outdoor2	1915 (139.4)	0.0030 (0.00025)	−19.2 (8.05)
SimRain	2327 (116.0)	0.0027 (0.00015)	−70.8 (7.43)
E11Immerse	2269 (137.1)	0.0061 (0.00042)	−46.0 (2.66)
Copper leaching model			
7dayImmerse	357 (18.9)	0.0020 (0.00019)	−455.4 (42.97)
100hrImmerse	253 (19.0)	0.0027 (0.00025)	−283.9 (34.69)
Outdoor1	235 (18.7)	0.0063 (0.00021)	19.2 (5.11)
Outdoor2	219 (18.8)	0.0050 (0.00025)	−17.4 (7.27)
SimRain	220 (17.5)	0.0047 (0.00015)	−47.5 (7.52)
E11Immerse	154 (18.8)	0.0093 (0.00042)	−38.3 (3.54)

Parameter estimates. Standard errors are shown in parentheses.

approach appears to be optimizing the leaching intervals because the E11Immerse method substantially underestimated long-term copper leaching, whereas the 7dayImmerse method overestimated both copper and boron leaching. The 100hrImmerse method appears promising, although further improvement may be possible by adjusting the length of the initial intervals. By using lumber-size specimens,

Table 3. Predicted cumulative leaching extrapolated over long-term exposures.

	Cumulative precipitation (mm)				95% Population prediction interval at 5000 mm	
Leaching method	500	1000	2000	5000	LPI[a]	UPI[a]
Cumulative boron leached (mg, % relative to Outdoor1)						
7dayImmerse	2442	2808	2917	2924	2679	3184
	158%	146%	142%	142%		
100hrImmerse	2050	2297	2355	2357	2095	2613
	133%	120%	115%	115%		
Outdoor1	1543	1919	2047	2057	1787	2307
	—	—	—	—		
Outdoor2	1509	1824	1910	1915	1669	2185
	98%	95%	93%	93%		
SimRain	1820	2193	2317	2326	1998	2543
	118%	114%	113%	113%		
E11Immerse	2188	2265	2269	2269	2115	2563
	143%	118%	111%	110%		
Cumulative copper leached (mg, % relative to Outdoor1)						
7dayImmerse	304	337	354	357	321	392
	136%	144%	150%	150%		
100hrImmerse	223	245	252	253	216	288
	100%	104%	107%	107%		
Outdoor1	224	235	235	235	199	271
	—	—	—	—		
Outdoor2	207	218	219	219	183	253
	91%	93%	93%	93%		
SimRain	203	219	220	220	187	254
	91%	93%	94%	94%		
E11Immerse	153	154	154	154	117	191
	68%	66%	66%	66%		

[a] Lower and upper prediction intervals.

and by relating hours of immersion to amount of precipitation, these immersion methods provide a reasonable means of estimating long-term leaching per unit surface area as a function of cumulative rainfall. This contrasts with the current AWPA E11 small cube method which causes rapid initial leaching that has no clear relationship with expected losses from wood products exposed to natural weathering. Although the total duration of the 100hrImmerse method is longer than that of the AWPA E11 method (approximately 38 d vs 14-17 d), no additional labor is required, and the time frame remains short when compared with that of standard laboratory methods for evaluating resistance to wood-attacking organisms.

CONCLUSIONS

The pattern and quantity of preservative leached from pressure-treated wood are a function of many factors, including preservative chemistry, wood species, wood dimensions, and the characteristics of the leaching environment. It is the latter factor that is most difficult to simulate, especially for wood exposed aboveground and subjected to intermittent wetting from precipitation. Ideally, an accelerated leaching method would allow estimation of preservative leaching as a function of the amount of rainfall at a specific location or climatic zone. Simulated rainfall is a logical approach, and our research has shown that a simulated rainfall method can closely emulate the quantity of preservative leached from lumber specimens exposed outdoors. However, that method is complex and may not be well suited for typical laboratory use or for standardization. This study demonstrated that much simpler immersion methods can also be used to provide useful estimates of leaching from wood products exposed to natural precipitation. The key features of these immersion methods are the use of larger specimen sizes that simulate lumber, and the extension of leaching intervals to allow wetting of the larger specimens and time for solubilized preservative components to diffuse to the wood surface. Analysis and modeling of data from the immersion methods indicate that time of immersion can be related to volume of precipitation, thus allowing prediction of leaching based on the rainfall characteristics of specific location or region. This study employed outdoor weathering near Madison, WI, and an alkaline borax–copper preservative; thus, the fit of the prediction will be somewhat influenced by the pattern of rainfall at a site (fewer, high-volume rainfall events vs extended periods of slow rainfall) and by characteristics of the preservative chemistry. It would be beneficial to have immersion leaching periods compared with natural leaching for other locations and other types of preservative chemistries.

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