ESTIMATING PRESERVATIVE RELEASE FROM TREATED WOOD EXPOSED TO PRECIPITATION[1]

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Abstract. Accelerated leaching methods are needed to better estimate emissions from treated wood used above ground or above water. In this study, we evaluated leaching methods using continuous immersion, dip immersion, and simulated rainfall approaches. Copper and/or boron emissions were measured for specimens treated with either chromated copper arsenate Type C (CCA-C) or a borax-copper (BC) preservative. The results of these leaching tests were compared with the extent of wetting and drying within the specimens and with the published reports of leaching and MC under natural exposures. Release per unit surface area was generally greatest with the simulated rainfall or constant immersion methods, but the relationship between the methods was dependent on the leaching characteristics of the specific preservative formulation. The lowest emissions were found for small specimens exposed to dip immersions. Comparison of the simulated rainfall results to published values indicates that the rainfall method and dip immersion scenarios underestimate copper release from wood exposed outdoors, and that the methods evaluated do not adequately simulate the wetting and drying conditions encountered in natural exposures. Further research is needed to better characterize the wetting and drying of in-service treated wood and to adapt test methods to more closely simulate these conditions.

Keywords: Leaching, methods, moisture content, precipitation, treated wood.

INTRODUCTION

Concerns about wood preservative leaching and environmental impact have primarily focused on preservative-treated wood that is immersed in water such as marine piles. In most structures, however, the greatest proportion of treated wood is not in direct contact with standing water or soil. The rate of leaching from treated wood exposed only to weathering is not easily determined because it is dependent on the pattern of precipitation and possibly on other climatic factors such as temperature, humidity, and ultraviolet radiation. Most studies of leaching caused by weathering have been conducted in outdoor exposures. Several studies have measured preservative concentrations in rainwater runoff from treated deck boards (Taylor and Cooper 2005; Garcia-Valcarcel and Tadeo 2006; Stefanovic and Cooper 2006), fence boards (Cooper and MacVicar 1995), deck sections (Taylor et al 1999; Cui and Walcheski 2000; Kennedy and Collins 2001; Choi et al 2004; Chung and Rud-

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dick 2004; Khan et al 2006), or shingles (Evans 1987). Although all of these studies have provided useful information on leaching rates under exposure conditions specific to that site and time, it is difficult to reproduce these tests or use the data to predict leaching rates under other weather conditions. In addition, the types of preservatives in treated wood are rapidly changing, and it is becoming less practical to conduct long-term in-service leaching studies of all new treatments.

Conventional accelerated laboratory methods of evaluating preservative leaching use continuous immersion of small specimens in either water (AWPA Method E11–06), soil (AWPA Method E20–06) (AWPA 2007), or severe weathering conditions (JIS K Standard 1571). Whereas these methods provide a conservative assessment of the ability of a preservative to provide long-term protection against biodeterioration, the relationship between results obtained with these methods and rate of leaching of preservatives from wood exposed to weathering is unclear. For example, these methods do not evaluate the effects of photodegradation, which has been shown to significantly increase leaching from wood treated with chromated copper arsenate (CCA) (Lebow et al 2003). An appropriate simulation of wetting and drying conditions is another challenge in developing a laboratory test to estimate preservative leaching from treated wood exposed to precipitation. Artificial rainfall approaches (Cooper and MacVicar 1995; Lebow et al 2003, 2004; Morrell et al 2004; Mitsuhashi et al 2007) have the advantage of simulating natural precipitation, but the methodology and equipment required are relatively complex. A less complex approach is to simulate precipitation by subjecting specimens to a series of short immersion periods with drying intervals between immersions. Such an approach using small specimens has been proposed for Organization for Economic Cooperation and Development (OECD) methods to estimate emissions from treated wood used above ground (Melcher et al 2004; Baines 2005; Schoknecht 2004, 2005; Temiz et al 2006).

In developing methods to estimate emissions from treated wood exposed to weathering, there is a need to balance simplicity with realistic simulation of wetting and drying conditions. In this article, we evaluate leaching methods using continuous immersion, dip immersion, and simulated rainfall approaches. The results of these leaching tests are compared with the extent of wetting and drying within the specimens and with the published reports of leaching and MC under natural exposures.

MATERIALS AND METHODS

Specimen Preparation

All specimens were cut from the sapwood of southern pine lumber. Specimen dimensions varied by leaching method, as shown in Table 1. Before treatment with preservative, the specimens were equilibrated at ambient indoor con-

Table 1. *Comparison of test conditions and specimen dimensions used in leaching trials.*

Test condition and specimen type	Dimensions (mm)	Specimens per treatment: Per container	Specimens per treatment: Total	Surface area of specimens in container ($\times 10^{-3}$ m^3)	Volume of specimens in container ($\times 10^{-3}$ m^3)	Ratio: surface area to volume
Constant immersion						
AWPA E11	19 × 19 × 19	6	30	13.0	41	0.32
Lumber (2 × 6)	38 × 140 × 254	1	5	90.3[a]	1352	0.07
Dip immersion						
Small flat	10 × 50 × 150	1	5	18.0[a]	75	0.24
Small EN113	15 × 25 × 50	5	25	20.0[a]	94	0.21
Lumber (2 × 6)	38 × 140 × 254	1	5	90.3[a]	1352	0.07
Simulated rainfall						
Lumber (2 × 6)	38 × 140 × 254	1	5	90.3[a]	1352	0.07

[a] Does not include the surface area of the ends, which were sealed to prevent water movement through the end grain.

ditions (6–10% MC). All specimens except the 19-mm cubes used in the AWPA E11 method were also end-sealed with neoprene rubber sealant before preservative treatment.

Preservatives and Treatment

Two types of preservative formulations were compared in this study. Chromated copper arsenate Type C (CCA-C), with an active composition of 47.5% chromium (CrO_3 basis), 34.0% arsenic (As_2O_5 basis), and 18.5% copper (CuO basis), was evaluated using a 1.0% solution concentration (equivalent to 0.15% elemental copper). The other preservative evaluated was an alkaline borax-copper formulation (BC) currently used for field treatment of utility poles. The BC was evaluated with a treatment solution containing 2.34% actives (equivalent to 0.25% elemental boron and 0.1% elemental copper). The mechanism of copper fixation in BC is thought to differ from that in CCA, thus providing the opportunity for comparison of copper release between the two formulations. To minimize variability in preservative distribution, all specimens were pressure-treated with a full-cell treatment process using a 30-min 81-kPa (gauge) initial vacuum followed by 60 min of pressure at 1034 kPa (gauge). Each specimen was individually weighed before and after treatment and to determine uptake of preservative solution. Copper retentions varied from 0.80 to 1.05 kg/m^3 for the CCA-treated specimens and from 0.56 to 0.73 kg/m^3 for the BC-treated specimens. Boron retentions in the BC-treated specimens varied from 1.38 to 1.81 kg/m^3. After treatment, the specimens were stored in plastic bags for 1 wk at ambient temperature to allow fixation reactions to proceed. The specimens were then allowed to air-dry to ambient indoor conditions (6–10% MC) before leaching.

Leaching and MC Methodologies

The leachate samples were analyzed for copper and/or boron by inductively coupled plasma emission spectrometry (ICP). Five replicates were used for each leaching and MC trial.

Continuous immersion of small cubes. This method followed AWPA Method E11, Standard Method of Determining the Leachability of Wood Preservatives (AWPA 2007). In brief, sets of six preservative-treated cubes were submerged in 300 mL of deionized water (Table 1). Immediately on immersion, the leaching container was subjected to a vacuum to withdraw the air from the wood and saturate the cubes with the leaching water. The containers were then subjected to mild agitation to ensure water movement. After 6, 24, and 48 h and subsequently at 48-h intervals, all of the leachate in the containers was collected for analysis and then replaced with an equivalent amount of deionized water. This process was repeated until the cubes had been leached for a total of 336 h (2 wk). Because of their small specimen dimensions and the initial vacuum impregnation with leaching water, the MC of the blocks typically exceeded 100% for the duration of the leaching trial.

Continuous immersion of lumber specimens. The leaching regimen was similar to that specified by AWPA Standard E11, except that the specimens were not vacuum-impregnated with water at the start of the test, and only one lumber specimen was placed in each leaching container. Each specimen was immersed in approximately 3500 mL of water (weighed to the nearest 0.1 g). The containers were then subjected to mild agitation to ensure water movement. The water was sampled and replaced after intervals of 6, 24, and 48 h and subsequently at 48-h intervals for a period of up to 2 wk. MC of each specimen was determined by weighing the specimens and then drying to constant weight in a 104°C oven.

Dip immersion—three specimen sizes. The leaching regime was patterned after approaches proposed for the OECD Guideline I (Melcher et al 2004; Schoknecht 2004, 2005). This approach attempts to simulate rainfall and subsequent drying events by subjecting small specimens to days with short immersion periods separated by several days of drying. Three specimen sizes were evaluated using this method (Table 1). The two smaller sizes have been proposed for use in

OECD Guideline I. The small flat specimen dimension was developed specifically for OECD Guideline I, whereas the small EN113 specimens are also used in evaluations of decay resistance (CEN 1996). Five of the EN113 specimens were placed in each leaching container and regarded as a single replicate. Lumber specimens were also included in the dip immersions to allow comparison with other methods used in this study.

Leaching consisted of 7 immersion days (Days 1, 4, 9, 14, 18, 25, and 30) spaced over a total of 30 da. For each immersion event, the specimens were placed in a shallow pan and covered with either 300 mL (small specimen sizes) or 1000 mL (lumber specimens) of deionized water for 60 min. The two immersion events on each immersion day were separated by 3 h, during which time the specimens were allowed to dry under room conditions. As proposed in the OECD Guideline (Melcher et al 2004; Schoknecht et al 2004), the leaching solutions from the two immersion events per day were combined to obtain one leachate sample per immersion day. MC was evaluated by weighing each specimen before and after each immersion. A subsequent shorter trial with more frequent weighing was conducted to obtain a more detailed MC trial for the smaller specimens. Average MC was calculated using a time-weighted mean based on linear interpolation between recorded measurements.

Simulated rainfall, lumber specimens. A simulated rainfall apparatus was used to spray fine droplets of deionized water at a rate of 3 mm/h onto a wide face of each specimen. The specimens were sprayed for 10.5 h/da for 4 da/wk (Monday through Thursday) for a total of 42 h/wk. All the water draining off each specimen was collected, and the water was not reused or recirculated. Between rainfall events, the specimens were left within their trays and allowed to air-dry, although the enclosure surrounding the specimens minimized airflow. A more detailed explanation of the simulated rainfall apparatus can be found in Lebow et al (2003). The MC developed in specimens subjected to simulated rainfall was evaluated in a separate 2-wk trial. Five southern pine sapwood specimens were placed into the artificial rainfall apparatus. The specimens were weighed immediately before each 10.5-h rainfall event at evenly spaced times within each rainfall event and immediately after the rainfall event. Average MC was calculated using a time-weighted mean based on linear interpolation between recorded measurements.

RESULTS AND DISCUSSION

Leaching

To allow more direct comparison between specimen sizes, leaching can be expressed on the basis of mass-per-unit surface area. As shown in Figs 1–3, quantities of copper and boron leached differed substantially between leaching methods. In each of these three figures, the bars show plus or minus one standard error. Days in test are offset slightly to aid in differentiating mean profiles.

Differences between methods were expected given the differences in specimen dimensions and exposure conditions. Release per unit surface area was generally greatest with the simulated rainfall or constant immersion methods, but it is apparent that the relationship between methods is dependent on the preservative formu-

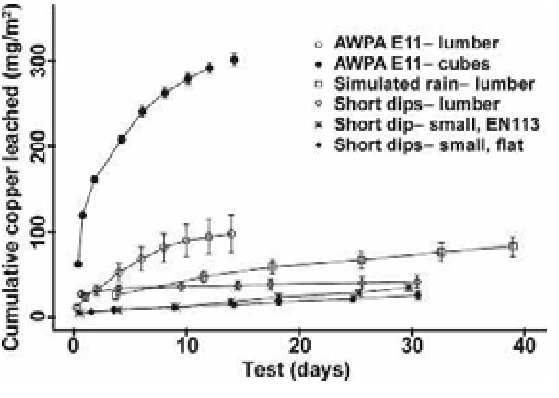

Figure 1. Cumulative release (mass-per-unit surface area) of copper from chromated copper arsenate-treated specimens. Days in test are offset slightly to aid in differentiating mean profiles.

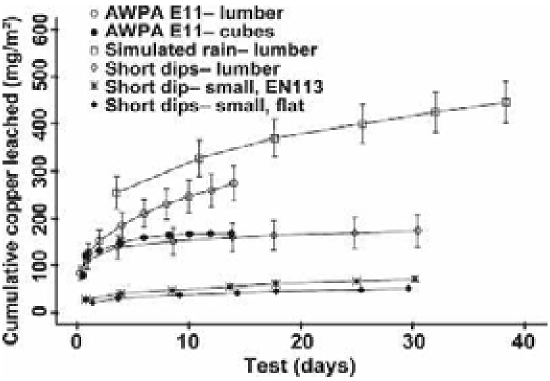

Figure 2. Cumulative release (mass per unit surface area) of copper from borax–copper-treated specimens. Days in test are offset slightly to aid in differentiating mean profiles.

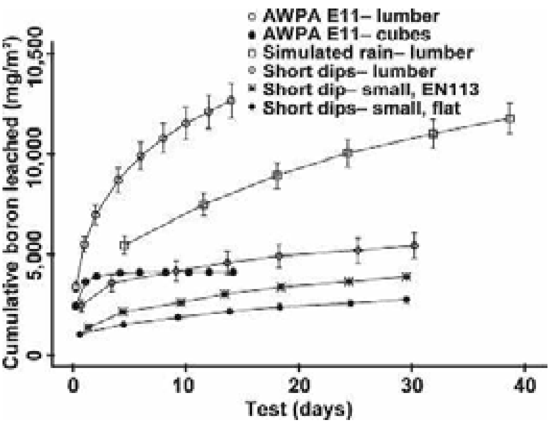

Figure 3. Cumulative release (mass-per-unit surface area) of boron from borax–copper-treated specimens. Days in test are offset slightly to aid in differentiating mean profiles.

lation and element of interest. The small size and high proportion of end grain in the 19-mm cubes used in the AWPA E11 method are intended to accelerate leaching; for copper release from CCA-treated wood, the AWPA E11 method clearly had produced the most leaching. For copper and boron from BC-treated wood, however, other methods produced greater cumulative release on a mass-per-unit area basis. A portion of this effect is attributable to differences in the volume of the specimens and the total mass of preservative available for leaching. The 19-mm cubes used in the AWPA E11 method have a smaller reservoir of available preservative than the lumber specimens. When compared on a percentage leached basis, leaching was greatest for the AWPA E11 method for all preservatives (Table 2). Nearly all the boron was leached from the 19-mm cubes, thus explaining the plateau in cumulative release that was reached within a few days (Fig 3). This finding demonstrates the importance of considering specimen volume and not only surface area when interpreting the results of leaching trials. It also indicates that larger "lumber" specimens may be desirable in developing leaching tests that estimate long-term release rates.

The early plateau and relatively low subsequent copper loss from the BC-treated 19-mm cubes (relative to that from CCA) is more difficult to explain, because approximately 90% of the copper remained in the cubes at the conclusion of the leaching test. For all other test methods, copper release from BC-treated wood was greater than that from CCA-treated wood, but none of the other methods removed more than 5% of the BC copper. It is possible that copper in BC-treated wood is present in two or more bonding environments, and that one form of copper is more readily removed. Once that fraction (in this case, approximately 10%) is exhausted, leaching is slowed.

The simulated rainfall method produced relatively high preservative losses in comparison with the dip immersion methods. Simulated rainfall also caused greater losses of copper from BC-treated wood than did constant immersion of lumber specimens. This effect is largely attributable to high losses of copper from the BC-treated specimens during the first week of simulated rainfall.

Not surprisingly, leaching from specimens exposed to short immersions was less than that from specimens exposed to constant immersion or simulated rainfall. Leaching was similar for the two small specimens sizes proposed for OECD Guideline I, although boron losses were slightly greater with the EN113 specimens. On a mass-per-unit area basis, releases tended to be greater from the lumber specimens subjected to short immersions than from the small specimens

Table 2. *Average total percentage leached and quantity leached at final sampling point.*[a]

Test condition and specimen type	CCA-Cu total (%)	BC-Cu total (%)	BC-B total (%)	CCA-Cu final mg/m^2	BC-Cu final mg/m^2	BC-B final mg/m^2
Constant immersion						
AWPA E11	11.8 (0.5)	9.5 (0.1)	94.5 (1.3)	9.5 (0.4)	0.5 (0.3)	1.1 (0.8)
Lumber (2 × 6)	0.7 (0.3)	3.0 (0.7)	55.8 (5.5)	3.4 (2.3)	15.5 (4.4)	551.6 (88.9)
Dip immersion						
Small flat	0.7 (0.2)	1.8 (0.2)	39.4 (3.3)	4.2 (1.2)	3.0 (0.4)	172.3 (33.0)
Small EN113	0.7 (0.2)	2.1 (0.3)	46.2 (2.3)	6.5 (1.9)	4.9 (0.8)	255.9 (25.3)
Lumber (2 × 6)	0.3 (0.1)	2.0 (0.7)	25.8 (2.9)	1.7 (1.3)	6.2 (0.9)	248.3 (69.5)
Simulated rainfall						
Lumber (2 × 6)	0.6 (0.2)	4.8 (0.8)	51.0 (3.8)	6.5 (2.5)	20.6 (6.9)	762.3 (98.9)

[a] Values in parentheses represent one standard deviation from the mean.
CCA, chromated copper arsenate; Cu, copper; BC, borax–copper; B, borax.

exposed to short immersions. This is understandable for boron losses, because the larger volume of the lumber specimens would have provided a greater amount of boron to replace that lost from the surface. It is less clear why this would be the case for copper depletion, because only a small fraction of copper was lost during the dip immersions. Differences in the proportions of grain orientation may have also affected preservative release, because previous research has indicated that radial preservative diffusion is greater than tangential diffusion in southern pine (Waldron et al 2005), probably because of the greater size and number of bordered pits on the radial cell walls.

One potential use of accelerated leaching data is to assume that the quantity released at the final sampling point is representative of the long-term release rate. This assumption is somewhat problematic because it does not allow for further declines in leaching, but it does provide a basis for comparison of the leaching methods. As shown in Table 2, quantities leached at the final sampling point varied widely among methods and preservative elements. The accelerated AWPA E11 method resulted in very low final leaching values for copper and boron from BC-treated wood but produced higher values than any other method for copper release from CCA-treated wood. The lumber immersion and simulated rainfall methods generally produced the greatest final release values for boron and copper from BC-treated wood. It is apparent that quantities released at the final sampling point are a function of specimen size, leaching condition, and the leach resistance of the preservative in question. Constant immersion of small specimens is likely to result in low final release values for more leachable preservative components. Mild leaching conditions such as short immersions prolong leaching from small specimens and result in somewhat greater final release values. Because they contain a greater reservoir of preservative, larger specimens subjected to more severe leaching conditions appear to result in the greatest final leaching values. The relationship among specimen size, leaching condition, and leach resistance of a particular preservative is complex. This is problematic when evaluating new types of preservatives for which leach resistance is unknown.

In evaluating applicability of these test methods to leaching in natural exposures, it is useful to compare leaching data from these methods with values reported for leaching from wood exposed outdoors. Researchers in Canada, Australia, Spain, and the US have reported on copper release from CCA- (or CCB-) treated specimens exposed horizontally for extended intervals. These studies have reported copper releases ranging from 0.21 to 0.64 mg/m^2/mm rainfall with an average of 0.47 mg/m^2/mm rainfall (Lebow et al 2000; Kennedy and Collins 2001; Taylor and Cooper 2005; Garcia-Valcarcel and Tadeo 2006; Stefanovic and Cooper 2006). Even after adjusting the surface area of specimens used in this study to discount the bottom surface, copper release obtained with simulated rainfall was only 0.18 $mg/m^2/mm$ rainfall. This release rate is lower than any of those reported for natural exposures. This indicates that although the simulated rainfall regime appeared rigorous in comparison with the dip immersion methods, it may underestimate in-service leaching. This finding also indicates that dip immersion methods are likely to substantially underestimate release from wood exposed horizontally outdoors unless multipliers (correction factors) are applied. However, as noted in this study, results of these leaching studies vary depending on mobility and fixation characteristics of each preservative. Thus, the appropriate multiplier/correction factor is not known until field exposure trials are conducted, and the assumption of a single correction factor for all new preservative systems is likely to result in over- or underestimation.

Simulation of Natural Moisture Fluctuations

One objective of any method to assess leaching caused by weathering is simulation of the wetting and drying conditions that occur in natural exposures. It is clear that vacuum impregnation and constant immersion methods as AWPA E11 can achieve and maintain unrealistically high MCs. The range of moisture contents obtained with dip immersion and simulated rainfall methods is less obvious. Because of their low volume, moisture uptake on the exterior of the small dip immersion specimens caused a rapid increase in MC (Fig 4). Maximum MCs observed with the small flat specimens were between 30 and 35%, whereas the maximums for the EN113 specimens averaged between 25 and 30%. However, the small specimens also dried rapidly, and the average overall MC of the specimens was less than 14% for the small flat specimens and less than 12% for the EN113 specimens. MCs for the dip immersion lumber specimens were lower because of their greater volume. The pattern of MC developed during the simulated rainfall regimen is shown in Fig 5. Because of the large specimen sizes, MC increased slowly and also decreased slowly during periods between rainfall events. The average maximum MC reached during the 2 wk of this evaluation was only 34%, but based on the pattern of weight gain and loss, it is probable that the average MC continued to increase with time. At the conclusion of the 6-wk leaching trial, the CCA-treated specimens were weighed and found to have an average final MC of approximately 49%.

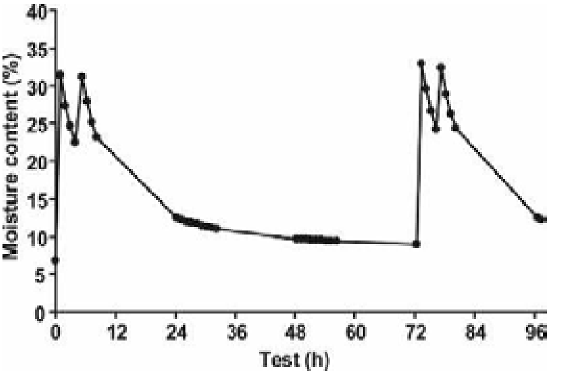

Figure 4. MC profile for untreated small (average of flat and EN113 specimens) exposed to short dip immersions. This pattern was repeated over the course of the test.

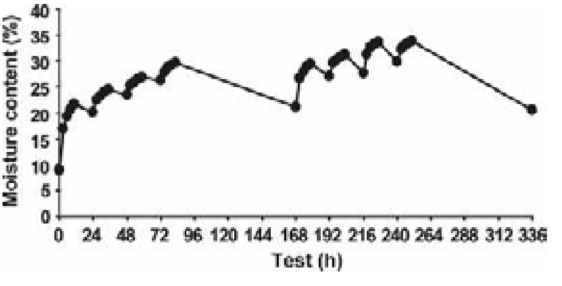

Figure 5. MC of untreated 38-mm × 140-mm × 254-mm pine sapwood specimens during exposure to 2 wk of simulated rainfall.

For comparison, previous researchers have reported that the MC of pine sapwood exposed to natural weathering may range from maximums of 80% to minimums of approximately 10% (Belford and Nicholson 1969; Edlund and Sundman 1989; Militz et al 1998; Rapp et al 2000; Lindegaard and Morsing 2003; Hedley et al 2004; Saladis and Rapp 2004; Rydell et al 2005). Most of the maximums reported fell within 40–55% for horizontal specimens and between 30 and 50% for vertical specimens.

Minimum MCs generally fell into the 10–15% range. Average MCs reported for horizontal exposures ranged 21–26%, whereas the averages reported for vertical exposure were 18.6 and 25.4%. Both maximum and average MCs observed using the dip immersion methods in this study were well below those reported for wood exposed outdoors and particularly less than those reported for wood exposed horizontally. It appears that the short immersions followed by rapid drying proposed for use in OECD Guideline I may underestimate the degree of wetting that occurs in natural exposures. For the majority of the test period, MC of the specimens is too low for diffusion or leaching processes to take place. It may be possible to improve this MC profile with adjustments to immersion and drying conditions. In contrast, it does appear that the simulated rainfall method can produce average maximum MCs at or above those reported for wood exposed outdoors. However, as conducted in this study, the simulated rainfall regimen did not replicate drying conditions and minimum MCs reported for natural weathering.

It is possible that leaching may have been greater from the simulated rainfall specimens if they had been allowed to dry to minimum MCs that more closely simulate natural rainfall conditions and experience a greater degree of check development. Checks may be an important factor in preservative leaching and redistribution because they increase surface area and allow precipitation ready access to the interior of treated products (Choi et al 2004; Taylor and Cooper 2005).

Photodegradation may also account for a portion of the greater losses reported in outdoor exposures. Ultraviolet (UV) degradation and the resulting erosion of degraded fiber are thought to cause a loss of approximately 0.03 mm of wood from the surface of CCA-treated wood each year (Feist and Williams 1991; Williams et al 2003). Depending on the leachate collection methods, small fibers or particles of eroded, treated wood may be collected with the leachate. The contribution of UV radiation and surface erosion to environmental releases is likely to be even greater in structures with foot traffic (Lebow and Foster 2005).

Because time is required for mobilized preservative components to diffuse through the wood to the surface, lower leaching from simulated rainfall may also result from the compressed timeframe. Although the volume of rainfall was similar to a year of exposure, the length of time for diffusion of mobilized components through the wood was shorter than that of a specimen exposed for a year outdoors. A compressed timeframe is, of course, the goal of accelerated testing, but application of accelerated leaching results for estimation of in-service leaching is far from obvious, and this is especially true when small specimens are used. In an effort to overcome this problem, Waldron et al (2005) have proposed a modeling approach to leaching estimation based on a preservative's availability and diffusion coefficients. Once certain preservative-specific parameters are determined, leaching can be estimated as a function of product dimensions and the length of time that the wood is sufficiently wet to allow diffusion.

Because the extent and pattern of preservative release is dependent on both test method and type of preservative, it is difficult to anticipate how well a particular test method will estimate long-term release from a new type of preservative. This problem suggests that it may be worthwhile to develop test methods that more closely simulate naturally occurring wetting and drying conditions. Artificial rainfall exposures have the potential for relatively close simulation of natural rainfall events and have the additional advantage of allowing extrapolation based on volume of rainfall. The dip immersion methods are simpler to conduct and have the potential for simulating natural wetting and drying conditions with adjustment of immersion scenarios. However, extrapolation of dip immersion leaching results to volume of rainfall expected for a given climate is less intuitive. Ideally, accelerated test methods would use large enough specimens and sufficient moisture changes to induce a degree of checking similar to that exhibited by treated products exposed in service. However, these conditions may be difficult to achieve in accelerated testing because large specimens are slow to gain and lose moisture. Other exposure factors that could affect leaching such as UV radiation and water characteristics (Kartal et al 2007) may also warrant consideration.

CONCLUSIONS

The quantity of preservative leached is a function of specimen size, type of leaching exposure, and the leach resistance of the preservative component in question. For the more leachable preservative components, constant immersion of lumber specimens or simulated rainfall on lumber specimens resulted in the greatest losses when calculated on the basis of mass-per-unit surface area. Although constant immersion of small specimens produced the greatest percentage loss of preservative, the small reservoir of available preservative resulted in lower releases when expressed on the basis of mass-per-unit surface area. These findings demonstrate the difficulty of extrapolating leaching rates from small blocks with a high proportion of end grain to commodity-size material. In contrast, the short dip immersions of small end-coated specimens resulted in the lowest preservative releases because insufficient water was absorbed. A comparison of the simulated rainfall results to published values indicates that the rainfall method evaluated and, by comparison the dip immersion scenarios, may underestimate copper release from wood exposed outdoors. Although the results of these accelerated tests can be adjusted to correspond more closely to actual exposures using correction factors or multipliers, this approach is problematic because the relationship between the accelerated test results and actual release is preservative-specific. Methods that more closely simulate natural wetting and drying conditions will help to minimize the under- or overestimation that is likely to occur when extrapolating results to long-term natural exposures.

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