# Environmental Degradation of Fiber-Reinforced Polymer Fasteners in Wood

Samuel L. Zelinka[1] and Douglas R. Rammer, M.ASCE[2]

**Abstract:** This paper examines the durability of fiber-reinforced polymer (FRP) nails in treated wood. The FRP nails were exposed to four conditions: (1) accelerated weathering, consisting of exposure to ultraviolet light and condensation; (2) 100% relative humidity (RH); (3) being driven into untreated wood and exposed to 100% RH; and (4) being driven into wood treated with alkaline copper quaternary (ACQ) and exposed to 100% RH. Changes in the physical, mechanical, and chemical properties were examined with weight loss, dynamical mechanical analysis (DMA), and near-infrared spectroscopy (NIR), respectively. Although fasteners exhibited changes after exposure to treated wood, the changes were not statistically different than the changes that occurred in untreated wood or in the humid environment. Under these three conditions, the fasteners gained 2–3% of their starting mass, and the storage modulus also increased by 20% after exposure. The results suggest that moisture is more important than the wood chemistry or preservative chemistry in determining the durability of FRP fasteners in wood. **DOI: 10.1061/(ASCE)MT.1943-5533.0000619.** © *2013 American Society of Civil Engineers.*

**CE Database subject headings:** Nails; Fastening; Fiber reinforced polymer; Coating; Wood; Degradation.

**Author keywords:** Nail; Preservative-treated wood; Dynamical mechanical analysis (DMA); Near-infrared spectroscopy (NIR).



## Introduction

Although not generally considered an aggressive environment, wood can be corrosive to metal fasteners if it is wet or has been treated with a wood preservative or fire retardant. Before 2004, the major wood preservative used in the United States was chromated copper arsenate (CCA) (Lebow 2004). The corrosion of metal fasteners in CCA-treated wood was examined extensively (Baker 1992), and it was found that fasteners made from hot-dip galvanized steel, stainless steel, silicon bronze, and copper gave adequate service life in CCA-treated wood (International Code Council 2003). However, in 2004, CCA was voluntarily withdrawn by industry for use in residential construction, and its market share has been taken up by a number of alternatives, such as alkaline copper quaternary (ACQ), copper azole (CA), and their corresponding micronized formulations (MCQ and MCA, respectively) (Lebow 2004).

The corrosiveness of alternatives to CCA has been researched heavily in the past 5 years because preliminary research ("Preservative treated wood" 2008) and anecdotal evidence (Burkholder 2004) suggested that these alternatives were more corrosive than CCA. This recent research has confirmed that, in most cases, these preservatives are more corrosive than CCA. For example, Kear et al. (2009) tested galvanized steel in many different preservative formulations and exposure conditions and found that ACQ-treated wood was between 3 and 19 times more corrosive than CCA, and that CA-treated wood was between 3 and 11 times more corrosive (the range represents differences in retention levels and exposure conditions). Similarly, Zelinka et al. (2010) found that CA and ACQ were 1.8 and 2.0 times more corrosive than CCA-treated wood for hot-dip galvanized fasteners exposed to a 100% relative humidity (RH) environment for 1 year. Zelinka and Rammer (2012) have examined the effect of corrosion rate on the degradation in lateral strength of joints in decks and shown that increasing the corrosion rate from 10 to 60 $\mu$m year$^{-1}$ decreases the time to failure by 500%. Because alternatives to CCA are more corrosive than CCA, and because this difference in corrosion affects the usable life of structures, corrosion of fasteners and joist hangers must be considered when designing and building with treated wood.

There are several ways to minimize corrosion in treated wood. Because the mechanism of corrosion in treated wood involves the reduction of cupric ions, metals noble to copper, such as stainless steel, have much lower corrosion rates in treated wood (Zelinka and Rammer 2009). Another option for minimizing corrosion is using a polymer- or ceramic-coated fastener to chemically isolate the metal from the treated wood. Finally, a completely nonmetallic fastener would be immune to traditional forms of corrosion.

Most of the focus on minimizing corrosion in wood has been on using either stainless steel or coated fasteners because these products dominate the market. However, there are disadvantages to these products. Stainless steel fasteners are several times more expensive than galvanized fasteners. Polymer-coated fasteners, although less expensive, are only as good as the polymer coating, which can be damaged before or during placement in wood. Zelinka et al. (2009) have shown that in some coated wood screws, the polymer coating can be entirely stripped when the screws are driven into the wood. Recently, a nonmetallic fastener has been introduced to the marketplace. This fastener, made from a fiber-reinforced polymer (FRP), by definition cannot experience corrosion because it is completely nonmetallic. It is also cheaper than stainless steel. Although the fastener is immune from corrosion, it may experience other forms of environmental degradation, such as crazing, embrittlement, or possibly even softening, in

[1]Materials Research Engineer, USDA Forest Products Laboratory, One Gifford Pinchot Dr., Madison, WI 53726 (corresponding author). E-mail: szelinka@fs.fed.us

[2]Research General Engineer, USDA Forest Products Laboratory, One Gifford Pinchot Dr., Madison, WI 53726.

Note. This manuscript was submitted on January 30, 2012; approved on June 14, 2012; published online on December 21, 2012. Discussion period open until October 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Materials in Civil Engineering***, Vol. 25, No. 5, May 1, 2013. © ASCE, ISSN 0899-1561/2013/5-627-631/$25.00.

treated wood. It is important to understand the durability of these nonmetallic fasteners as the fasteners become established in the marketplace.

This paper examines the durability of a commercial FRP nail for potential use in treated wood by exposing the fastener to different environments, including treated and untreated wood. As opposed to metals, for which weight loss is proportional to the amount of corrosion (degradation) that occurred, a simple weight-loss measurement would not be able to capture the degradation of a FRP nail. For this reason, the chemical, mechanical, and physical properties of FRP nails were quantified before and after the exposures. Although the interpretation of these chemical and physical changes is more nuanced than just a simple weight loss, these measurements give clues to the various changes that might occur to the FRP fasteners in wood.

## Methods and Materials

### Fasteners

One type of commercially available nonmetallic fastener was examined. The material safety data sheet revealed the fastener was a composite of a high-strength polymer and fiberglass dust. Fasteners were approximately the size of a common 8d nail and had rectangular cross-sections that were 3.2 by 2.6 by 56.9 mm in length and weighed 0.686 g (median of 100 measurements). Ten fasteners (replicates) were tested in each exposure condition.

### Exposure Conditions

The fasteners were subjected to one of four different environmental exposure conditions in a laboratory setting: accelerated weathering, 100% relative humidity, untreated wood, or ACQ-treated wood. A detailed explanation of these exposure conditions is given in this section.

The accelerated weathering exposure test followed the ASTM G154 (ASTM 2006) protocol with a modified temperature during the condensing cycle. The fasteners were exposed to $0.89\ \mathrm{W/m^2/nm}$ of irradiance using ultraviolet A (UVA) 340 bulbs for 8 h at 60°C followed by a 4-h-long dark cycle in which water condensed on the fasteners at 40°C. These cycles were repeated until the combined exposure totaled 1,000 h. Fasteners were suspended on sample racks and exposed directly to the UV radiation (not embedded in wood).

Fasteners were exposed to 100% RH to examine their moisture resistance. Fasteners were tested by suspending the fasteners over a reservoir of water in a sealed desiccator at 27°C; the resulting relative humidity within the desiccator was 100%, as dictated by the Gibbs phase rule. Fasteners were exposed for 6 months.

The solid wood exposure tests (untreated and ACQ-treated wood) closely followed common procedures for measuring the corrosion of metallic fasteners embedded in treated wood (Zelinka 2007; Zelinka and Rammer 2009; Zelinka et al. 2010). The fasteners were hand-driven into predrilled holes in blocks of southern pine (*Pinus* spp.) (38 by 50 by 90 mm) that had been equilibrated at 27°C and 90% RH before the exposure test. Predrilled holes were either exactly the largest dimension of the nails or, in some cases, 0.4 mm (1/64 in.) oversized. It was found that the fasteners would fracture if driven into undersized holes or directly into the pine. These wood/fastener assemblies were then placed in a desiccator suspended over a reservoir of water with a resulting relative humidity of 100% at 27°C. To minimize experimental differences, all of the lumber was purchased at the same time, and half of the lumber was treated to $4\ \mathrm{kg\,m^{-3}}$ ACQ (carbonate formulation), the suggested retention for aboveground use (American Wood Protection Association 2007). Fasteners were exposed for 6 months, after which they were carefully removed by sawing grooves in the wood near the fastener, placing the wood in a vise, and extracting the fastener by hand.

### Property Evaluation

Before and after the fasteners were exposed, their physical, mechanical, and chemical properties were evaluated to detect changes caused by the exposure. Physically, the fasteners were examined for swelling caused by water uptake by measuring the fasteners to the nearest 0.01 mm at four key points along the length of the fasteners before and after exposure; these points are illustrated in Fig. 1. Likewise, the fasteners were weighed to the nearest 0.1 mg before and after exposure to see whether they gained weight (water uptake) or lost weight (environmental degradation).

Changes in the surface chemistry were measured with near-infrared spectroscopy (NIR) using an ASD AgriSpec spectrophotometer (Analytical Spectral Devices, Boulder, Colorado), capable of measuring wavelengths from 350–2,500 nm with a 10-mm spot size. The light source was provided with a tungsten halogen bulb that was fed through a fiber-optic sampling probe to deliver illumination to the physical sample. The reflected light from the sample was carried by a separate fiber-optic bundle to the spectrophotometer. The baseline spectrum was obtained by measuring a white reference, and this spectrum was automatically applied and subtracted to each raw spectrum. Because the fastener was smaller than the spot size, a special methodology was developed. The fastener was placed in a special white reference with a groove machined in it so that the fastener would lay flat. The grooved reference also assured that the spot region before and after exposure would be the same. Spectra were collected over the 10-mm spot size, which included both the nail and the white reference. To isolate changes in the surface chemistry of the fastener, spectra were taken before and after exposure using the same white reference, and relative differences between spectra were examined. Specific peaks were located and identified using the freely distributed *Extrema* program written for *MATLAB Release 14* (MathWorks 2004).

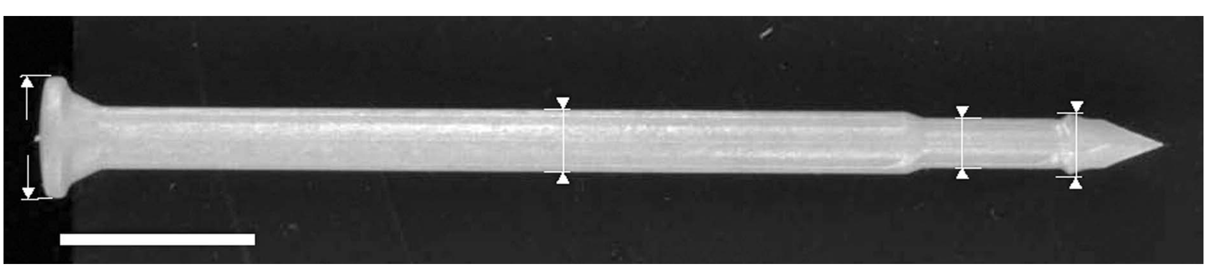

**Fig. 1.** Fiber-reinforced polymer fastener with location of diameter measurements marked (scale bar represents 10 mm)



J. Mater. Civ. Eng. 2013.25:627-631.

**Table 1.** Absolute and Percentage Change in Mass and Dimensions of Fasteners for Different Exposure Conditions

| Exposure condition | Mass (mg) | Length (mm) | Diameter (mm) by location number[a] | | | |
|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 |
| Original values | | | | | | |
| 100% RH | 687 (1.2) | 56.85 (0.01) | 6.17 (0.004) | 3.17 (0.005) | 2.56 (0.007) | 3.02 (0.013) |
| ACQ-treated wood | 687 (1.2) | 56.85 (0.03) | 6.17 (0.005) | 3.16 (0.005) | 2.56 (0.004) | 3.04 (0.007) |
| Untreated wood | 687 (1.2) | 56.87 (0.02) | 6.17 (0.004) | 3.16 (0.005) | 2.57 (0.005) | 3.04 (0.010) |
| Accelerated weathering | 686 (0.3)[c,d] | 56.92 (0.03) | 6.16 (0.002) | 3.16 (0.004) | 2.56 (0.005) | 3.03 (0.003) |
| Absolute changes | | | | | | |
| 100% RH | 16.3 (0.1)[b] | −0.08 (0.04) | 0.02 (0.005) | −0.03 (0.01) | −0.02 (0.01) | 0.04 (0.02) |
| ACQ-treated wood | 14.4 (0.7)[b] | −0.20 (0.17) | 0.01 (0.01) | −0.01 (0.02) | 0.00 (0.01) | −0.08 (0.05) |
| Untreated wood | 14.8 (0.1)[b] | −0.27 (0.17) | 0.00 (0.01) | −0.02 (0.01) | 0.00 (0.01) | −0.12 (0.04) |
| Accelerated weathering | −6.2 (0.15)[d] | −0.17 (0.02) | −0.02 (0.003) | −0.02 (0.004) | −0.02 (0.004) | −0.03 (0.003) |
| Relative changes | | | | | | |
| 100% RH | 2.4% | −0.2% | 0.31% | −0.84% | −0.69% | 1.30% |
| ACQ-treated wood | 2.1% | −0.4% | 0.19% | −0.24% | 0.10% | −2.77% |
| Untreated wood | 2.2% | −0.5% | 0.02% | −0.64% | −0.04% | −3.85% |
| Accelerated weathering | −0.9% | −0.3% | −0.39% | −0.72% | −0.84% | −0.92% |

Note: Numbers in parentheses represent standard error.
[a]Locations associated with location numbers are shown in Fig. 1.
[b]Grouping (i) from Tukey's HSD test.
[c]Grouping (iii) from Tukey's HSD test.
[d]Group (ii) from the Tukey's HSD test represents no difference from the original/preexposure mass.



Changes in the mechanical properties were measured using dynamical mechanical analysis (DMA). Fasteners were placed in the tension fixture of a Q800 dynamic mechanical analyzer (TA Instruments, New Castle, DE). A frequency sweep was performed from 0.1–100 Hz with 10 measurements per decade of frequency at 35°C. The storage modulus, $E'$ (i.e., the in-phase component of the dynamic modulus), and the loss modulus, $E''$ (the out-of-phase component of the dynamic modulus), were recorded at each frequency step.

## Results and Discussion

### *Physical Changes*

Changes in the dimensions and weights of the fasteners are summarized in Table 1. Practically speaking, the dimensions of the fasteners exposed to the 100% RH, ACQ-treated wood, and untreated wood conditions remained the same before and after exposure. For these fasteners, some of the fasteners slightly elongated in one dimension, whereas others decreased in size. The average change in any given dimension was very close to the standard error of the measurements. Although in some cases the relative changes appear to be nonnegligible (i.e., several percent), it is only because the starting dimensions were so small (3 mm) that slight fluctuations in the absolute dimensions cause a large percentage shift. It should be stated, however, that the fasteners exposed to accelerated weathering experienced consistent shrinkage. Although this change was only a few hundredths of a millimeter, it occurred nearly identically for all fasteners, and, unlike the other exposure conditions, no fasteners elongated. It therefore appears that the fasteners slightly shrink with exposure to accelerated weathering and that the other exposure conditions cause small positive and negative fluctuations in diameter.

Although the fasteners seem dimensionally stable for the most part, there was a noticeable and statistically significant change ($\alpha = 0.05$) in mass for each of the exposure conditions. Differences among groups were analyzed using Tukey's honestly significant difference (HSD) test ($\alpha = 0.05$, groups indicated in Table 1). The fasteners exposed to 100% RH, ACQ-treated, and untreated wood gained more than 2% of their starting mass and were statistically different than the control (unexposed) fasteners, but variations among these three treatments were not statistically different. The increase in mass in these groups most likely arises from water ingress into the fasteners. In contrast, the fasteners exposed to accelerated weathering with UV light lost nearly 1% of their starting mass, which suggests some UV attack of the fasteners. It should be stated that, as part of the ASTM G154 (ASTM 2006) protocol, these fasteners were cycled through condensing periods in which the RH was 100% at 40°C, so one would expect that these fasteners would have gained mass like those exposed to the 100% RH for 6 months, all other things being equal. Therefore, it is possible

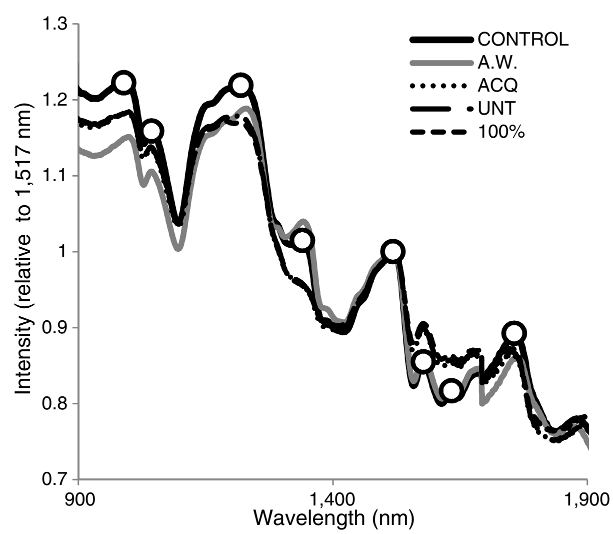


**Fig. 2.** Near-infrared spectroscopy spectra for FRP nails before (CONTROL) and after being exposed to accelerated weathering (A.W.), driven in ACQ-treated wood (ACQ), driven into untreated wood (UNT), or exposed to 100% RH (100%) (black dots correspond with peaks listed in Table 2)



J. Mater. Civ. Eng. 2013.25:627-631.

**Table 2.** Wavelength ($\lambda$) and Peak Intensity ($I$) for Peaks in NIR Reflectance Spectra

| Peak | Control $\lambda$ (nm) | Control $I$ (arb) | Accelerated weathering $\lambda$ (nm) | Accelerated weathering $I$ (arb) | ACQ-treated wood $\lambda$ (nm) | ACQ-treated wood $I$ (arb) | Untreated wood $\lambda$ (nm) | Untreated wood $I$ (arb) | 100% RH $\lambda$ (nm) | 100% RH $I$ (arb) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 989 | 1.22 | 996 | 1.15 | 993 | 1.20 | 991 | 1.18 | 994 | 1.19 |
| 2 | 1,044 | 1.16 | 1,044 | 1.10 | 1,042 | 1.15 | 1,042 | 1.13 | 1,042 | 1.14 |
| 3 | 1,219 | 1.22 | 1,229 | 1.19 | 1,217 | 1.20 | 1,214 | 1.17 | 1,213 | 1.18 |
| 4 | 1,336 | 1.02 | 1,341 | 1.04 | — | — | — | — | — | — |
| 5 | 1,518 | 1.00 | 1,517 | 1.00 | 1,519 | 1.00 | 1,519 | 1.00 | 1,519 | 1.00 |
| 6 | 1,578 | 0.86 | 1,579 | 0.86 | 1,578 | 0.90 | 1,578 | 0.90 | 1,578 | 0.90 |
| 7 | 1,633 | 0.82 | 1,633 | 0.82 | 1,630 | 0.86 | 1,630 | 0.86 | 1,629 | 0.86 |
| 8 | 1,756 | 0.89 | 1,762 | 0.86 | 1,751 | 0.86 | 1,751 | 0.87 | 1,750 | 0.87 |

Note: Data are normalized to peak intensity at 1,518 nm; arb = arbitrary.



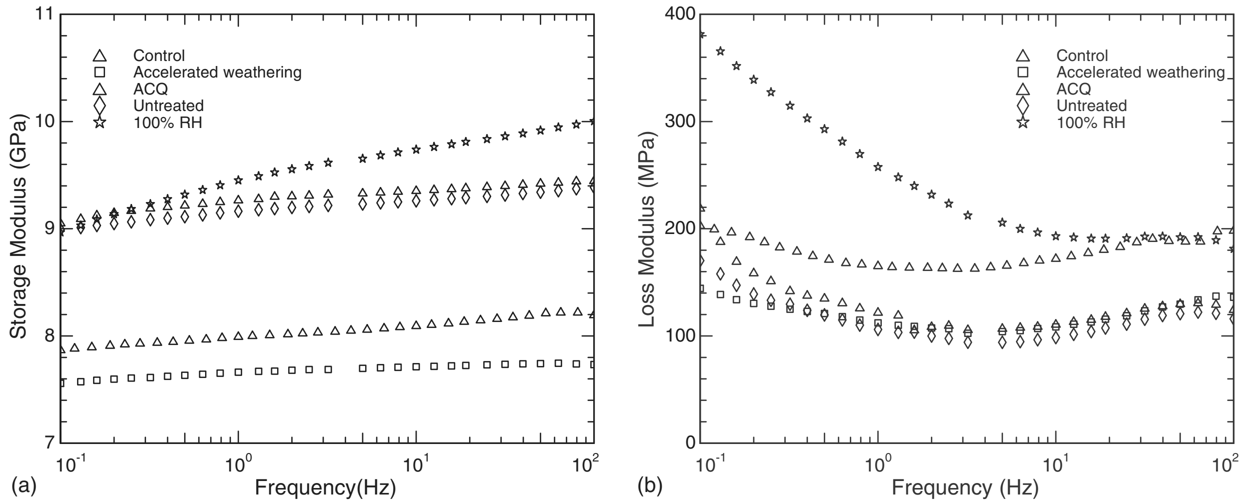


**Fig. 3.** Moduli for control and exposed fasteners: (a) storage; (b) loss

that the fasteners would have lost more mass if the accelerated weathering test did not have the condensing periods.

### *Chemical Changes*

The pretest NIR spectra were similar across all specimens except for some small differences in intensity between spectra that manifested themselves as slight distortions along the *y*-axis. To make the data analysis easier, the *y*-axis data were scaled by the intensity of the peak at 1,518 nm. Once scaled, the data were virtually identical; the coefficient of variation of the peak with the biggest variability was at most 0.04%. The peak at 1,518 nm was chosen to normalize the other peaks because it was clearly identifiable and remained at nearly the same frequency and intensity after all exposures.

The scaled NIR spectra are shown in Fig. 2. The NIR spectra for the control fasteners exhibited eight distinctive peaks, which are highlighted with black dots in Fig. 2. The frequency and intensity of each peak are summarized in Table 2 for each treatment. Most of the changes that occurred during the exposure test were minor; the peaks were shifted in either intensity or frequency by a small amount.

The most noticeable feature from the NIR spectra was the peak at 1,336 nm, at which there was a distinct behavior difference between exposure conditions. The fasteners in the control group exhibited a peak at 1,336 nm, which became more prominent after exposure to accelerated weathering. However, this peak was not present in those fasteners exposed to ACQ-treated wood, untreated wood, or 100% RH.

**Table 3.** Storage and Loss Moduli at 1 Hz Determined from DMA

| Exposure condition | Storage modulus (GPa) | Loss modulus (MPa) |
|---|---|---|
| Control | 8.0 (0.2)[a] | 160 (10) |
| Accelerated weathering | 7.6 (0.3)[a] | 160 (20) |
| Untreated wood | 9.0 (0.2)[b] | 120 (20) |
| 100% RH | 9.2 (0.2)[b] | 290 (20) |
| ACQ-treated wood | 9.2 (0.2)[b] | 120 (10) |

Note: Numbers in parentheses represent standard error.
[a]Grouping (a) from Tukey's HSD test.
[b]Grouping (b) from Tukey's HSD test.

### *Mechanical Changes*

The storage and loss moduli are shown in Fig. 3 for typical curves for each exposure condition. The storage modulus was nearly constant across the frequencies tested, increasing very slightly with frequency; the slope was dependent on exposure condition. Likewise, the loss modulus decreased slightly with frequency, and the amount of decrease also depended on exposure conditions. Because there were no peaks in the frequency spectra, the data can be compared at a given frequency to make data easier to examine.

The storage and loss moduli (taken at 1 Hz) are presented in Table 3. Control fasteners had a storage modulus of 8.0 GPa. Fasteners exposed to accelerated weathering had a lower, but not statistically different, storage modulus, whereas fasteners exposed to treated wood, untreated wood, and 100% RH had a statistically significant higher storage modulus.



J. Mater. Civ. Eng. 2013.25:627-631.

## Summary and Conclusions

The purpose of the investigation was to examine the compatibility of a nonmetallic fastener for use in treated wood. After 6 months' exposure to treated wood, small but noticeable changes occurred in physical, chemical, and mechanical properties of the fasteners. These changes were similar to the changes that occurred to fasteners that were placed in untreated wood and fasteners exposed to the 100% relative humidity environment in which the wood was conditioned. It therefore appears that most of the changes observed during the exposure period are caused by moisture. Wet conditions caused the fasteners to have a higher storage modulus and caused the peak at 1,336 nm in the NIR spectra from the control group to disappear. From the perspective of using FRP fasteners in treated wood, the data after 6 months suggest that their performance would not be much worse than if the FRP fasteners were used in wet or humid environments.

## Acknowledgments

The authors acknowledge funding from the Federal Highway Administration National Historic Covered Bridge Research Program.

## References

American Wood Protection Association (AWPA). (2007). "Use category system." *AWPA U1-06*, Granbury, TX.

ASTM. (2006). "Standard practice for operating fluorescent light apparatus for UV exposure of nonmetallic materials." *ASTM G154*, West Conshohocken, PA.

Baker, A. J. (1992). "Corrosion of nails in CCA- and ACA-treated wood in two environments." *For. Prod. J.*, 42(9), 39–41.

Burkholder, M. (2004). "CCA, NFBA, and the post-frame building industry." *Frame Build. News*, 16(5), 6–12.

International Code Council (ICC). (2003). *International building code*, Delmar Cengage Learning, Florence, KY.

Kear, G., Wu, H.-Z., and Jones, M. S. (2009). "Weight loss studies of fastener materials corrosion in contact with timbers treated with copper azole and alkaline copper quaternary compounds." *Corros. Sci.*, 51(2), 252–262.

Lebow, S. (2004). "Alternatives to chromated copper arsenate for residential construction." *Res. Pap. FPL-RP-618*, USDA, Forest Service, Forest Products Laboratory, Madison, WI.

*MATLAB 14* [Computer software]. MathWorks, Natick, MA.

"Preservative treated wood." (2008). *Simpson Strong-Tie Technical Bulletin*, Pleasanton, CA.

Vargas-Aguilera, C. A. (2007). "Extrema. Matlab central file exchange." MathWorks, Inc. ⟨http://www.mathworks.com/matlabcentral/fileexchange/12275⟩.

Zelinka, S. L. (2007). "Uncertainties in corrosion rate measurements of fasteners exposed to treated wood at 100% relative humidity." *J. Test. Eval.*, 35(1), 106–109.

Zelinka, S. L., Ortiz-Candelaria, L., Stone, D. S., and Rammer, D. R. (2009). "Electrochemical impedance spectroscopy (EIS) as a tool for measuring corrosion of polymer-coated fasteners used in treated wood." *For. Prod. J.*, 59(1–2), 77–82.

Zelinka, S. L., and Rammer, D. R. (2009). "Corrosion rates of fasteners in treated wood exposed to 100% relative humidity." *J. Mater. Civ. Eng.*, 21(12), 758–763.

Zelinka, S. L., and Rammer, D. R. (2012). "Modeling the effect of nail corrosion on the lateral strength of joints." *For. Prod. J.*, 62(3), 160–166.

Zelinka, S. L., Sichel, R. J., and Stone, D. S. (2010). "Exposure testing of fasteners in preservative treated wood: Gravimetric corrosion rates and corrosion product analyses." *Corros. Sci.*, 52(12), 3943–3948.



J. Mater. Civ. Eng. 2013.25:627-631.