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The effect of moisture content on the corrosion of fasteners embedded in wood subjected to alkaline copper quaternary treatment

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ABSTRACT

This paper characterizes the corrosion rate of embedded fasteners as a function of wood moisture content using gravimetric and electrochemical measurements. The results indicated that the corrosion rate increased with moisture content before reaching a plateau. The phases present in the corrosion products, as analyzed using X-ray diffraction, are generally consistent with previous work. Uniform corrosion was observed for all fasteners and all conditions except steel fasteners embedded in water-saturated wood. Data of dependence of corrosion rate on moisture content, presented herein, are necessary to ensure the accuracy of combined hygrothermal/corrosion models used to predict durability of wood structures.

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1. Introduction

Moisture plays an important role in the corrosion of metals in wood. Wood is a hygroscopic material and freely exchanges water with the environment, establishing an equilibrium moisture content (MC, defined as the ratio of the mass of water to the mass of dry wood, expressed either as a percentage or decimal) that depends upon the temperature and relative humidity of the ambient air, and also on its previous moisture history of the wood. Metal fasteners in wood can therefore be exposed to moisture conditions that could lead to corrosion [1–17]. However, when the wood moisture content is low, there may be a threshold moisture content below which fasteners do not corrode in wood [11,18–23]. The first work that suggested a threshold for corrosion was performed by Baechler [19,20] who examined the corrosion of fasteners in wood that was in equilibrium with air at 30% relative humidity (RH), 65% RH, 90% RH and an outdoor exposure. For untreated pine (*Pinus ponderosa*), the corrosion rate was zero for the 30% RH and 65% RH conditions, but jumped to 6 μm year^{-1} at 90% RH (approximately 20% MC) [24]. Baechler observed similar trends for wood treated with zinc chloride. Kear et al. measured the corrosion rate of steel and galvanized steel fasteners in untreated pine (*Pinus radiata*) and pine treated with chromated copper arsenate (CCA), alkaline copper quaternary (ACQ), and copper azole (CA) conditioned at 75% RH, 90% RH, and “moisture saturated air” [11]. Corrosion at 75% RH (approximately 14% MC) was nearly undetectable. These gravimetric tests suggest that corrosion of embedded metals begins to occur when wood is in equilibrium with a relative humidity of 70–75%. However, the data collected in these gravimetric tests are too sparse to understand how the corrosion rate changes above the threshold. Other researchers have used electrochemical test methods to better understand the role of moisture on metals corroding in wood.

Dennis et al. used polarization resistance measurements at many moisture contents to examine how the corrosion rate changes with moisture content in CCA treated wood [22]. A zinc coupon was used as a working electrode and was placed between two sections of treated wood, one side of which had a salt bridge to a reference electrode. The moisture content was lowered from near saturation to 15% MC by letting the wood air dry in a “semi-sealed container”. It was then raised back to saturation by placing it in a 100% RH environment and removing it in intervals for measurement. Importantly, the wood was not allowed to reach equilibrium except near saturation and at 15% MC. We replot their data of the corrosion current density (which is proportional to the corrosion rate) as a function of moisture content in Fig. 1. The corrosion rate exhibits hysteresis when plotted against moisture content, which is not physically meaningful. This most likely arises from the fact that the wood was not in equilibrium when the measurements were taken. The corrosion rate has a sigmoidal dependence on moisture content with a threshold at 15% MC and a plateau above

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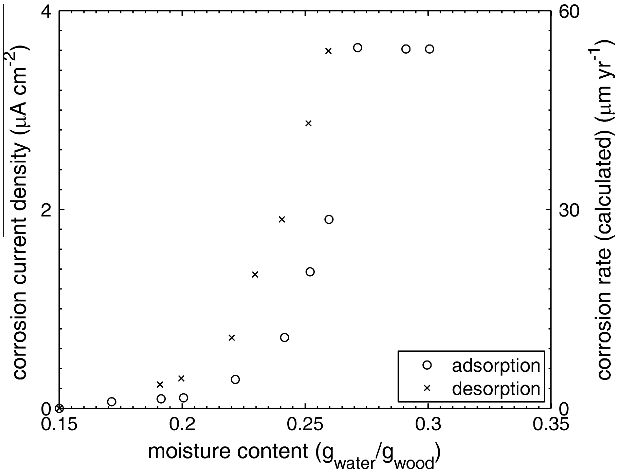

Fig. 1. Corrosion current density, as a function of wood moisture content as measured by Dennis et al. [6] for galvanized steel in contact with wood treated with CCA from polarization resistance measurements.

25% MC. These data are consistent with the observations from gravimetric tests; however, because of the number of conditions tested a more detailed curve could be developed.

The data of Dennis et al. [22] exhibit a sigmoidal dependence on moisture content. In general data with this shape can be fit by an equation of the form

$$R = \frac{A}{1 + \exp[B(C - M)]} \tag{1}$$

where the corrosion rate, R, depends upon the moisture content M, and A, B, and C are fitting parameters that represent the asymptotic maximum corrosion rate, the steepness of the transition from zero corrosion rate to the maximum, and the location of the transition, respectively. Zelinka et al. [25] have used Eq. (1) to predict the corrosion rate (R) of embedded fasteners as a function of moisture content (M). The parameters B and C describing the steepness and location of the transition were taken from a fit of the data of Dennis et al. [22]. The asymptotic corrosion rate at very high moisture content (A) was taken from corrosion rates measured electrochemically in water-extracts of treated wood, which were shown to have corrosion rates similar to those measured gravimetrically in solid wood exposed to 100% relative humidity [26–29]. Eq. (1) was implemented as a post-processor in a hygrothermal model; the hygrothermal model calculates the wood moisture content using hourly climatic data, and the post-processor calculates the amount of corrosion. The accuracy of this method is limited in part by the lack of data on the corrosion rate as a function of moisture content.

While previous studies have shown that the corrosion rate increases with moisture content up to a plateau (resulting from fiber saturation of the wood), it is unclear whether the mechanism of corrosion also changes with moisture content. The only work that examined the corrosion products of metals embedded in treated wood was performed by Zelinka et al. [27], who used X-ray diffraction to identify the corrosion products of fasteners embedded in wood exposed to 100% relative humidity. Under these conditions, the corrosion products that form on fasteners embedded in wood differ from those that form in atmospheric corrosion. These differences both affect the corrosion rate and relative performance of steel and galvanized steel fasteners [27]. For fasteners embedded in wood and exposed to a 100% relative humidity environment, smithsonite ($ZnCO_3$), the passivating, protective zinc corrosion product [30,31], did not form which resulted in the galvanized fasteners corroding more rapidly than steel fasteners [27]. It is not clear if the same corrosion products form at all moisture contents, or if this only occurs at 100% relative humidity.

This paper investigates the corrosion kinetics and corrosion products of fasteners embedded in wood through a combination of gravimetric and electrochemical measurements. One goal of the work is to develop more data that can be used in combined hygrothermal–corrosion modeling. The work builds upon previous studies that examined corrosion at different relative humidities [11,19,20] but extends into the over-hygroscopic region. In addition, the work adds to the very limited knowledge of the corrosion products that form on metals embedded in wood.

2. Methods and materials

Two complementary methods were used to evaluate the dependence of corrosion rates on wood moisture content: exposure tests, in which fasteners were embedded into wood and exposed at one of four moisture conditions for a year, and electrochemical tests, in which small metal coupons were held against the wood specimens and polarized. In addition, the corrosion products on the fasteners used in the exposure test were examined.

All wood specimens were cut from a single beam of southern pine, believed to be slash pine (*Pinus elliottii*). In the time between sawmilling and transit to the laboratory, the beam was partially infected with a blue stain fungus; whether blue stain has any effect on corrosion is unknown, but blue stain contamination is common in commercially available lumber. For the exposure test, wood specimens were cut along the anatomical planes of the wood to 38 mm (tangential) by 89 mm (radial) (nominal US "2 × 4") by 610 mm (longitudinal) and the fasteners were driven into a purely tangential face. The specimen size was chosen to correspond with the ASTM G198 standard [32]. The specimens used in the electrochemical test were cut into small 25 mm by 25 mm blocks with a thickness in the longitudinal direction of 9.5 mm. All wood specimens were treated with waterborne alkaline copper quaternary (type D) as specified in AWPA standard P5 [33]. The composition of the preservative consists of 66.7% copper oxide and 33.3% didecyldimethylammonium carbonate dissolved in ethanolamine. The treatment was performed by submersing the wood in a treatment solution, pulling a vacuum (20 kPa absolute pressure) for 30 min, followed by applying a pressure of 1034 kPa for 60 min. The targeted preservative retention was 4 kg of wood preservative m^{-3} of wood, which was the recommended preservative retention for above ground use [34] at the time this study was initiated; the calculated actual preservative retention based upon solution uptake was 3.5 kg m^{-3}. This preservative retention corresponds to approximately 1.9 kg of elemental copper m^{-3} of wood.

2.1. Exposure test

Four different moisture conditions were tested, all at 27 °C. The first two conditions were equilibrium conditions achieved by placing the wood specimens in environmental chambers maintained at 90% RH and 95% RH, respectively. The specimens were allowed to come to equilibrium prior to the driving of fasteners into the specimens. Wood moisture contents remained stable for each specimen throughout the test, and replicate specimens had roughly the same moisture contents. For the third condition, specimens were first equilibrated at 95% RH. Fasteners were then driven and specimens were placed in a desiccator above a reservoir of water (100% RH). These specimens had small differences in moisture content among replicates. The fourth condition was obtained by submerging end-sealed specimens under water for several days. Fasteners were then driven and wood specimens were placed in a sealed container in contact with a small amount of liquid water (100% RH). These