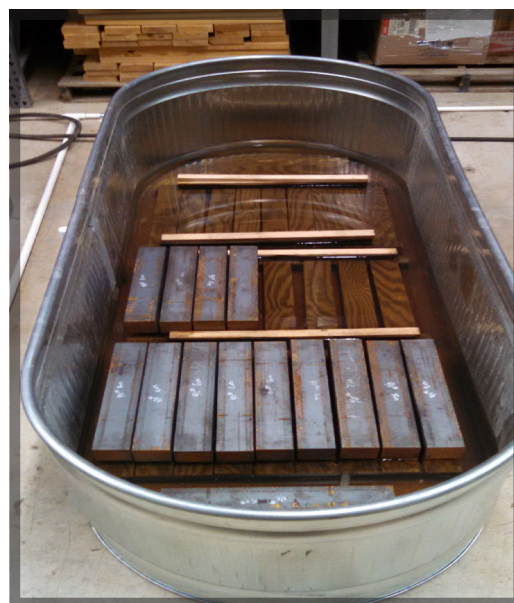
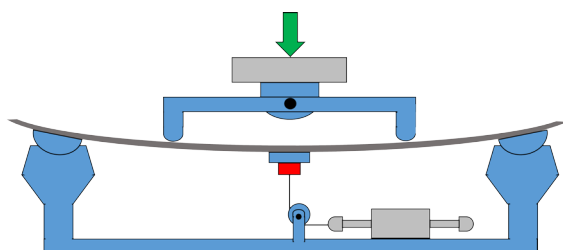
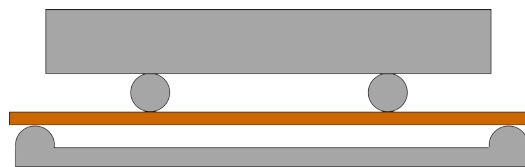
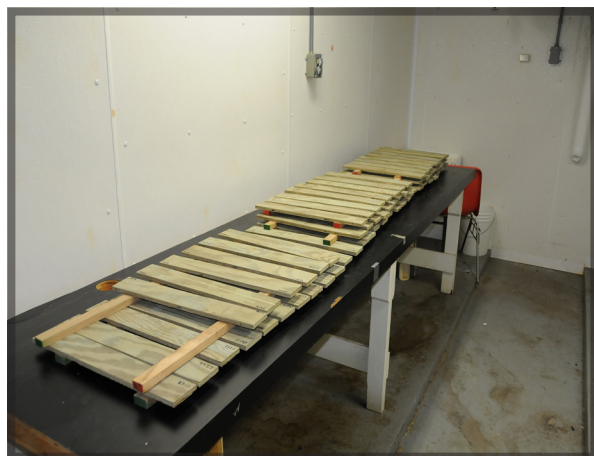




United States Department of Agriculture

Accelerated Aging of Preservative-Treated Structural Plywood

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Abstract

In this study, the changes in physical properties and preservative retention of high-grade plywood when subjected to artificial aging processes were examined. The plywood was 15/32-in.-thick panels manufactured from southern yellow pine A and C grades of veneer. The artificial aging processes consisted of three primary mechanisms of degradation: thermal degradation, hydrolysis, and swelling and shrinking stresses. Three aging processes of various severity were used. The least severe was cycled changes in ambient temperature and humidity. The second most severe was cycles of submersion and air-drying. The most severe was cycles of soaking first under a vacuum then under high pressure to elevate the moisture content, followed by oven-drying. Additional parameters explored included the effects of continuous load versus no load during the aging processes, and the effects of salt water versus fresh water on the high-pressure soaking. After artificial aging, the plywood was tested in flexure and tensile shear. The changes in the plywood physical properties and preservative levels with respect to the increasing number of artificial aging cycles were recorded and analyzed.

Keywords: artificial aging, plywood, flexural strength, tensile-shear, preservative retention, CCA, moisture cycling, temperature cycling

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English unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
pound (lb), mass	0.45359	kilogram (kg)
pound per square inch (lb/in ²)	6.894	kilopascal (kPa)
pound per cubic foot (lb/ft ³)	16.018	kilogram per cubic meter (kg/m ³)
ounce (oz)	28.4	gram (g)
fluid ounce (fl oz)	0.03	liter (L)
T_{F}	$T_{\text{C}} = (T_{\text{F}} - 32)/1.8$	T_{C}

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1. Introduction

It is critical to know how wood products will perform during their service life, specifically how aging will affect performance characteristics of these products. This type of information is important to both manufacturers and users of wood products. To collect this information with in-service products would be very time consuming and cost prohibitive. Therefore, scientists and engineers rely on test methods that accelerate the aging process. From accelerated aging tests, scientists and engineers can estimate the service life of a particular product.

Gillespie (1984) presents a historical perspective on the development of accelerated aging concepts to estimate service life of wood- and fiber-based materials and states that the fundamental purpose of accelerated aging is to evaluate a material or portion of a structure for its durability, serviceability, or long-term performance. Numerous technical reports and publications that summarize results of research studies aimed at developing these concepts—from addressing concerns about paper-based materials for library or archival storage to assessing the long-term performance of structural composite materials—are reviewed and serve as the foundation for Gillespie (1984). Those reports and publications are included in this report, listed in Additional References.

Subsequent research papers summarized studies that focused on development of test methods for accelerated aging (Inoue 1992, Hua and Wang 1988, Saad and others 2016), relationship with in-field aging of wood-based materials (Krahmer and others 1992, Okkonen and River 1996, River 1994), and evaluation of new products, adhesive systems, or preservative treatments with established test methods (Furuta and others 2013, Sellers 1989, Sellers and others 1990, Sellers and Gardner 1989, Oh and Lee 2004).

The USDA Forest Service, Forest Products Laboratory (FPL), recently completed a laboratory study designed to examine the accelerated aging of preservative-treated structural plywood. The flexural and tensile-shear properties of samples of chromated copper arsenate (CCA) treated plywood were evaluated after exposure to several

accelerated aging tests. This report summarizes the design of the study and results obtained.

2. Materials and Methods

This section describes the materials, material handling, aging treatments, and testing procedures used in this study. Figure 1 is a flow chart of the study.

2.1. Materials

The plywood panels examined in this study were 4- by 8-ft plywood panels of 15/32-in. thickness and were constructed of southern yellow pine veneer. Veneer visual grades A and

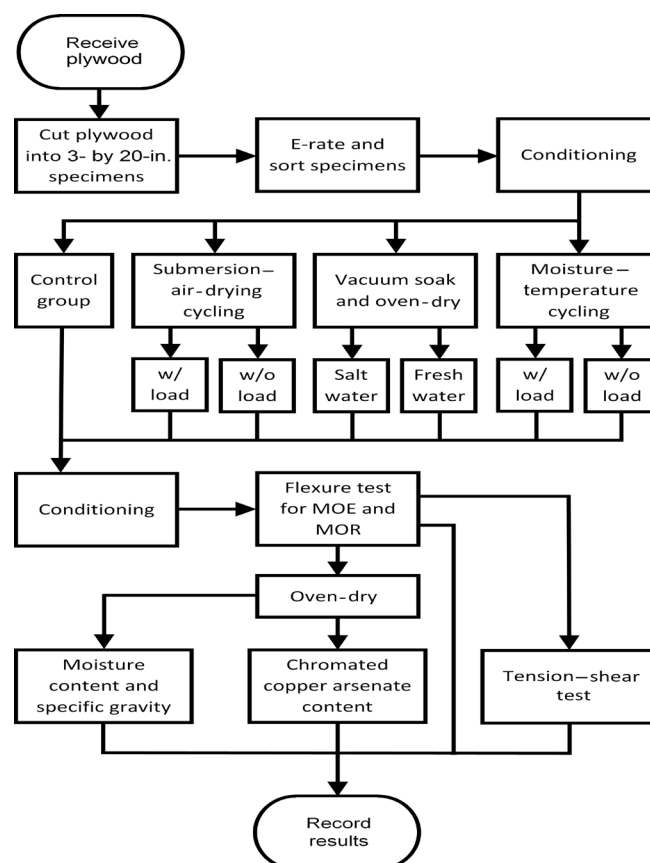


Figure 1—Project flow chart.

C were used. The panels were treated with a CCA Type C wood preservative to a target retention level of 1 lb/ft³ of panel. The resulting panels were rated for exterior exposure.

Upon arrival at FPL, seven plywood panels were taken from the supplied shipment of panels and assigned letter identifiers A through G. From each 4- by 8-ft panel, 56 specimens measuring 3 in. wide by 20 in. long were cut. A total of 392 specimens were obtained from panels A through G. Approximately 6 months into the study, the scope was expanded and additional specimens were needed; therefore, three additional plywood panels were selected, labeled H through J, and cut into 176 specimens with dimensions of 3 by 20 in.

To minimize property variation among the groups, the specimens were presorted based on dynamic modulus of elasticity (MOE) using the stress wave timing technique (Ross 2015). The dimensions and mass of each specimen were measured and the density calculated. A Metriguard 239A Stress Wave Timer was used to measure the transit time of stress waves along the length of the specimens. From the transit time, the stress wave velocity for each specimen was calculated. The stress wave velocity and density were used to calculate dynamic MOE as shown in Equation (1):

$$E = \rho c^2 \quad [1]$$

where E is dynamic MOE, ρ is wood density, and c is stress wave velocity.

The specimens were ordered according to dynamic MOE and then distributed into each of the five groups, which resulted in each group having a similar range and distribution of dynamic MOE values. After each group was subjected to its respective aging process, the specimens were brought into a conditioning room set at constant 70 °F and 65% relative humidity (RH). The specimens remained in the conditioning room for 2 weeks to approach an equilibrium moisture content of approximately 12%. After conditioning, the specimens were tested to obtain material properties.

2.2. Aging Treatments

Artificial aging treatments for plywood primarily use three sources of degradation: thermal degradation, hydrolysis, and swelling and shrinking stresses (Gillespie and River 1976). Exposure to elevated temperatures accelerates temperature effects that would be experienced in service. Hydrolysis is a chemical breakdown of a compound while interacting with water and can degrade glues used to construct plywood. Swelling and shrinking stresses can cause internal damage to the plywood, which weakens the structure and degrades the plywood material characteristics. Combinations of these factors have been used in artificial aging procedures for more than 50 years to simulate exposure during in-service use (Gillespie 1965). Several factors contribute to in-service exposure including location, weather, temperature, and

function. Plywood in service for a year in Phoenix, Arizona, will probably look different than a similar piece in service for a year in Gulfport, Mississippi. When possible, material properties of artificially aged plywood should be compared with plywood taken from in-service use to determine the severity and duration of artificial aging processes needed to achieve properties similar to those of the in-service pieces.

In this study, five specimen groups were constructed from the specimens cut from plywood panels A through G. The five groups included a control group and four other groups to undergo different aging treatments. The aging treatments were moisture–temperature cycling (MT), moisture–temperature cycling with load (MT+L), vacuum soak–oven-dry (VSD), and vacuum soak with salt water and oven-dry (VSD+S). Three specimen groups were constructed from the specimens cut from plywood panels H through J. The three groups included a submersion control group and two other groups to undergo aging treatments submersion unloaded (SU) and submersion loaded (SU+L). The submersion control group and the original control group were statistically compared, and no statistical difference was found between the groups at 95% confidence interval; therefore, the original control group and the submersion control group were combined into a single combined control group, which, hereafter, is referred to simply as the control group. The total number of specimens per group and the number of spare specimens are shown in Table 1.

2.2.1. Moisture–Temperature Cycling and Moisture–Temperature Cycling under Load

The first accelerated aging exposure consisted of moisture–temperature cycling both unloaded and under load. This type of exposure degrades the plywood via both thermal degradation and contributes to shrinking and swelling stresses. During the MT aging process, plywood specimens were placed in a temperature- and humidity-controlled chamber. The room environment alternated between a 15-day period of high humidity and high temperature (HH) and a 15-day period of low humidity and low temperature (LL). The prescribed conditions during the HH cycle were 80% ± 5% RH and a temperature of 90 ± 6 °F. The conditions during the LL cycle were 50% ± 5% RH at a temperature of 70 ± 6 °F. One HH and one LL period constituted a single cycle. Figure 2a shows the plywood specimens in the temperature- and humidity-controlled chamber.

In addition to the MT aging process, a sample group (MT+L) was subjected to temperature and moisture cycling while placed under constant load. The MT and MT+L aging processes occurred in the same chamber; therefore, the environmental conditions and cycle durations were identical for both groups. A 40-lb weight was placed on each specimen in a manner analogous to the subsequent flexure test (Fig. 3). Figure 2b shows the MT+L samples in the environmental chamber.

Table 1—Number of specimens in each group

Specimen group	Number of groups	Specimens per group	Spares	Total	Specimens tested per group		
					Flexure	CCA ^a retention	Tensile –shear
Control	1	62	0	62	62	10	20
Moisture–temperature cycling	4	15	10	70	15	3	10
Moisture–temperature cycling + load	4	15	5	65	15	3	10
Vacuum soak–oven-dry	5	10	5	55	10	3	10
Vacuum soak–oven-dry + salt	5	10	5	55	10	3	10
Submersion unloaded	4	15	0	60	15	3	10
Submersion loaded	4	15	0	60	15	3	10

^aCCA, chromated copper arsenate.

Fluctuation in chamber temperature and RH measured during the aging process is shown in Figure 4. Additional temperature and RH data are provided in Appendix A. The temperature remained within the prescribed range during 96% of the aging process; it fell below the range 3% of the time and was above the range <1% of the time. The RH remained within the prescribed range during 63% of the process; it fell below 20% of the time and was above the range 16% of the time. The effect of the RH being out of prescribed range would be a lessening of the severity of the aging process. Specimens were subjected to 3, 6, 9, or 12 cycles. At the end of the prescribed number of cycles, specimens were removed from the humidity chamber and placed in a conditioning room at 70 °F and 65% RH for a period of 2 weeks prior to material property testing.

2.2.2. Submersion Unloaded and Loaded

The second accelerated aging exposure consisted of submersing plywood samples in a water tank both unloaded and loaded. This method is used to investigate how the combination of hydrolysis and shrinking and swelling stresses degrade the mechanical performance of plywood. During the submersion aging process, plywood specimens are subjected to periods of complete submersion in water purified through reverse osmosis filtering followed by a period of air-drying.



Figure 2—Plywood specimens in a humidity- and temperature-controlled chamber: (a) unloaded specimens; (b) specimens loaded with 40-lb weights.

Large tanks were set up to hold the specimens during the aging process (Fig. 5a). The room holding the tanks was a temperature- and humidity-controlled chamber with temperature set to 73 °F and 50% RH. The tanks contained unloaded and loaded specimens as shown in Figure 5b. For the loaded specimens, a 40-lb weight was placed on each specimen in a manner analogous to the subsequent flexure test shown in Figure 3. The water level was sufficiently high to completely submerge the plywood specimens but was below the rectangular bar stock comprising the majority of the load. The specimens were submerged until the following three criteria were met: (1) a minimum of 3 days had passed, (2) the change in specimen weight was less than 4% for two consecutive measurements taken 24 hours apart, and (3) a moisture content (MC) of 65% was achieved. Unloaded specimens were used only to monitor the criteria because it was necessary to keep the loaded specimens under stress continuously for the duration of the cycles. After all three conditions were satisfied, the tanks were drained and the specimens were allowed to air-dry until the previously mentioned conditions one and two were met or the original specimen weights prior to the start of the submersion aging process were achieved. A period of

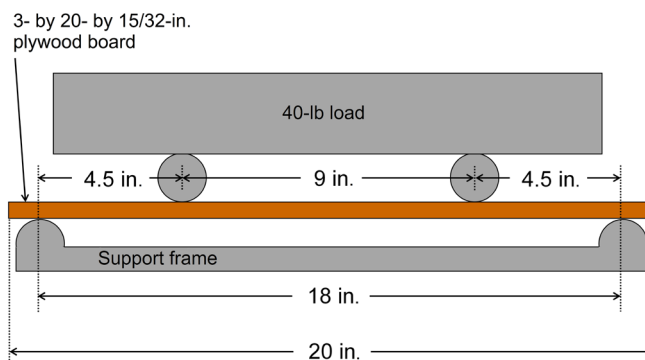


Figure 3—Moisture–temperature cycling under load (MT+L) plywood specimens under constant load.

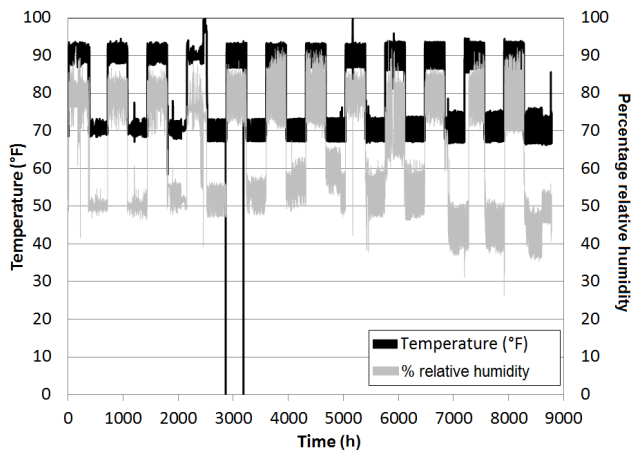


Figure 4—Temperature and percentage relative humidity (%RH) during moisture–temperature (MT) and moisture–temperature under load (MT+L) aging processes.

submersion followed by a period of air-drying constituted a single cycle. Specimens were subjected to 3, 6, 9, or 12 cycles. At the end of the prescribed number of cycles, specimens were removed from the humidity chamber and placed in a conditioning room set at constant 70 °F and 65% RH for approximately 2 weeks prior to material property testing.

The average MC of the sampled specimens at the end of the wet portions of the cycles was 68%, with a range between 59% and 75%. The MCs at the end of the wet portion of three of the twelve cycles were below 65% and measured 59%, 62%, and 64%. Criteria 1 and 2 were satisfied during wet portions of all cycles. The average MC of the sampled specimens at the end of the dry portions of the cycles was 20%, with a range between 18% and 23%. Criteria 1 and 2 were satisfied during dry portions of all cycles.

2.2.3. Vacuum Soak–Oven-Dry with and without Salt

The third accelerated aging exposure is a widely used procedure for accelerated aging of plywood that involves exposing plywood specimens to a series of alternating vacuum soaking in water purified through reverse osmosis filtering and oven-drying cycles. This method is used to investigate how the mechanical performance of the plywood specimens changes when exposed to all three forms of degradation: thermal, hydrolysis, and shrinking and swelling stresses. A second set of tests were performed that were identical to the first with the exception that salt was added to the purified water. It was hypothesized that the salt would provide an additional avenue for degradation by mechanical destruction of the wood cells through formation of salt crystals during the drying process, chemical breakdown of the wood in the presence of salt solution, or both. The VSD+S aging process was expected to be the most severe of all the aging processes; the VSD process was expected to be less severe than the VSD+S but more severe than the other aging processes. In this study, specimens were subjected to cycles of vacuum impregnation with warm (100 °F) water,



Figure 5—Tanks containing submersion plywood specimens: (a) all tanks in the temperature- and humidity-controlled chamber; (b) layout of submersion unloaded (SU) and submersion loaded (SU+L) specimens in the tank.

which better replicates expected in-service conditions, followed by oven-drying at 180 °F. Separate procedures were conducted using purified (reverse osmosis) water and a salt solution composed of purified water and 35,000 ppm salt (NaCl). The salt used was Morton (Chicago, IL) Culinox 999 Food Grade Salt, which contains no iodide or other additives. The specimens were sorted and assigned into groups of 10, as previously described, for exposure to either 5, 10, 20, 30, or 40 cycles of soaking and drying. The specimens were initially conditioned at 68 °F and 65% RH, weighed, and measured for length, width, and thickness.

The objective of the vacuum soaking was to increase the MC of the plywood above the fiber saturation point of 30%. Preliminary trials demonstrated that this could be readily achieved with a 30-min initial vacuum followed by immersion and a 30-min equilibration at atmospheric pressure. In each of two preliminary trials, three specimens were vacuum-soaked and allowed to surface-dry and cool for 1 h. Moisture meter pins were driven to the midpoint of the plywood thickness on three locations on both wide faces (six total measurements per specimen). The moisture meter used was a Protimeter Timbermaster, Model BLD5604 currently manufactured by Amphenol Advanced Sensors (Wallingford, CT). The electrodes were Hammer Electrode, Model BLD5055, with insulated pins. Although resistance-based volumetric moisture meters become less accurate above the fiber saturation point, the values observed indicate volumetric MCs well in excess of 30%. Previous research indicates that the presence of CCA wood preservative has relatively little effect on resistance-based moisture meter measurements (Richards 1990).

Prior to vacuum impregnation, the specimens were bundled into groups of 10 and spaced to allow fluid flow between the specimens. The bundles were secured to a stainless steel rack that was placed into the stainless steel vacuum cylinder. Plastic mesh was placed between the specimens to ensure water access to all surfaces. An initial 30-min vacuum at -11.7 lb/in^2 (gauge) was applied to the specimens followed by introduction of preheated water (100 °F) while still under vacuum. After the specimens were fully immersed, the vacuum cylinder was vented to atmospheric pressure and the specimens remained submerged for an additional 30 min. The temperature of the water was

maintained during the immersion period by steam coils within the vacuum cylinder. Following the immersion period, the specimens were removed from the cylinder and allowed to air-dry 4 h to allow time for excess water to leave the specimens. They were then dried for 18 to 24 h in a forced air-drying oven maintained at 180 °F. Following drying, the specimens were returned to the vacuum cylinder for vacuum impregnation. After five vacuum impregnation–oven-drying cycles, one set of 10 specimens was removed from the group and returned to the conditioning room to await mechanical properties testing. Subsequent sets of 10 specimens were removed after 10, 20, 30, and 40 cycles. Water was reused during several vacuum impregnation cycles. The same water was used for cycles 1 through 5. After five vacuum impregnation cycles, the water was changed for fresh purified water because most of the water soluble wood extractives and poorly fixed preservative components would have been freed within the first five cycles. The same water was used for cycles 6 through 40.

2.3. Test Procedures

2.3.1. Flexure Tests

Two-point flexure tests were conducted in accordance with ASTM D3043, Method B (ASTM 2011b). A diagram of the test setup is shown in Figure 6a. In Figure 6b, a photograph of the actual test setup is shown. The span between supports was 18 in. on center. The rocking support surfaces allowed the plywood specimen to remain in flat contact across the support surface throughout the test. The two load points were spaced 9 in. from each other and 4.5 in. from each support. The two load points were connected through a pivot point to the moving cross head, and a load cell on the cross head measured the load during testing. The measured load was recorded electronically. To monitor deflection, a steel 1/2-in. washer was affixed to the bottom surface of the plywood specimen using hot melt glue. The washer was placed at the specimen midpoint with respect to both the longitudinal and lateral axes. A string was connected between a linear variable differential transformer (LVDT) and a rare earth magnet. The LVDT was affixed to the load frame beneath the plywood specimen. The rare earth magnet

was placed in contact with the washer on the plywood specimen. This configuration allowed the center deflection of the plywood specimen to be measured by the LVDT directly and eliminate any concerns regarding compliance in the load frame and test setup during loading. The deflection was recorded electronically.

2.3.2. Tensile–Shear Tests

After the plywood specimens were tested in flexure, a portion of the specimen was used to conduct a tensile–shear test. Tensile–shear tests were conducted in accordance with ASTM D906-98 (ASTM 2011a). The purpose of this test was to estimate the relative performance of the adhesive bond in plywood. Five pairs of tensile–shear tests were performed on each artificially aged group. The control group had 10 pairs of tensile–shear tests, as shown in Table 1. All specimens were conditioned (73 °F and 63% RH) prior to testing. The testing apparatus and custom grips are shown in Figure 7.

A 3.25-in. portion of the failed flexure specimen was selected to construct the tensile–shear specimens. The portion selected was between the inner and outer locations of loading during the flexure test as shown in Figure 8a,b. The removed portion was then cut into smaller segments measuring 3.25 by 1 in. as shown in Figure 8c. The specimens were prepared per ASTM D906 part 6, with the notches cut so as to test both lathe check directions (check pulled open and check pulled closed), as shown in Figure 8d,e. The peak load in pounds and the percentage wood breakage were determined from the tensile–shear tests. The peak load was recorded during the tensile–shear test, and the percentage wood breakage was visually estimated after the test was completed.

2.3.3. Preservative Retention

The CCA retentions were determined by inductively coupled plasma atomic emission spectroscopy (ICP), as explained in American Wood Protection Association (AWPA) methods A7 (digestion) (AWPA 2014a) and A21 (ICP analysis) (AWPA 2014b).

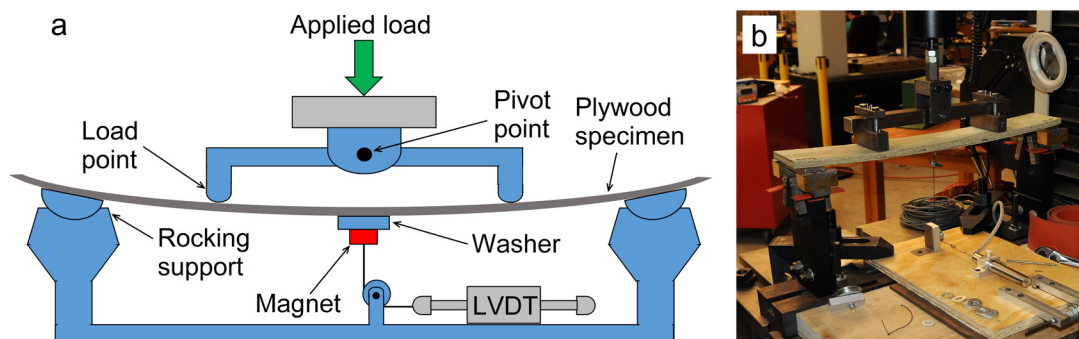


Figure 6—Plywood specimen flexure test setup: (a) diagram of setup; (b) actual test setup.

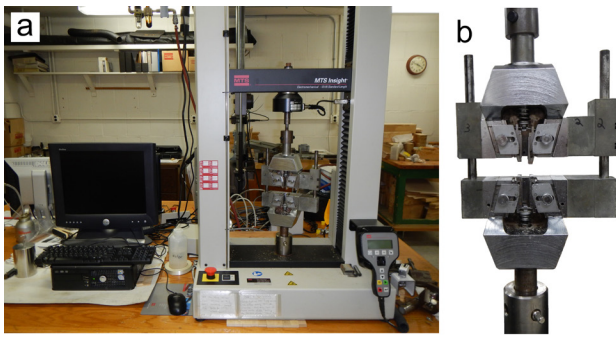


Figure 7—Tensile-shear testing equipment: (a) test of setup; (b) custom shear grips.

To prepare the samples for ICP, wood samples weighing approximately 0.018 oz were digested by placing them into 0.17 fl. oz of nitric acid (70% concentration). The solution was heated with microwave radiation to 302 °F for 20 min under pressure and then brought up to 1.7 fl. oz volume with water. The 0.018-oz samples were removed from the outer ply of the plywood. In some cases, a 0.018-oz splinter was digested. However, in most cases, the wood was ground to 20 mesh (0.0331-in. openings) in a Wiley mill prior to digestion to homogenize any spatial distributions of the elements within the wood. Duplicate samples from the same ply were run for each condition as a quality control check.

The digested solution was then run through the ICP. The signal intensities for each element were compared with calibration curves created with five known concentrations to determine the sample concentration, which resulted in the elemental concentrations for chromium, copper, and arsenic (in ounces of element per ounces of wood).

To calculate the CCA retention, the elemental compositions were converted to the equivalent amount of metal oxide. These could then be used to calculate the CCA retention based on the concentration of each element by the ratio of the elemental oxides for CCA-C specified in AWPAP5 (AWPA 2014c) and the oven-dry specific gravity of the wood (taken as 0.5). This resulted in three CCA retentions (one based on each element), which were averaged to give the reported CCA concentration.

3. Results and Discussion

3.1. Flexure Test

Flexure testing methods are discussed in Section 2.3.1 and were used to determine specimen MOR and static MOE properties. The load and displacement data were exported into a spreadsheet program in which they were used to calculate the stress and strain during testing. The MOR was the maximum stress achieved during the testing. The MOE was the slope of the stress-strain curve between 20% and 40% of the MOR. The average, standard deviation (SD), and coefficient of variance (COV) were calculated for each group. Tables of these values are shown in Appendix B. Tables B1 through B3 show values for MOR and MOE,

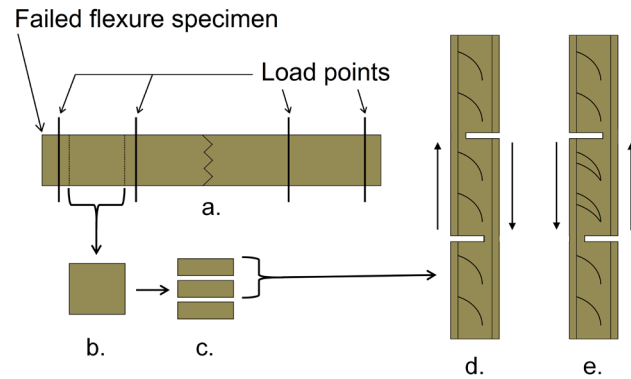


Figure 8—Tensile-shear test specimens: (a) failed flexure specimen showing locations of loading during test; (b) removed portion between loading locations; (c) removed portion cut into sized coupons; (d) tensile-shear specimen notched so lathe checks are pulled closed; (e) tensile-shear specimen notched so lathe checks are pulled open.

which were derived from the raw data collected during the flexure testing.

The MOR values for the MT, MT+L, SU, and SU+L groups are shown in Figure 9. The symbols indicate the average values for the aged groups. The vertical bars extending from the symbols indicate the range of values for the aged group. Although a noticeable drop occurs between the control and the 3-cycle group, there is not a noticeable continuing downward trend for the 6-, 9-, and 12-cycle groups. The average values for the MT and MT+L groups tended to be higher than those of the SU and SU+L groups.

The MT and MT+L cycles had a deleterious effect on the MOR of the plywood specimens, but a definitive trend did not appear. The largest magnitude drop in average MOR for

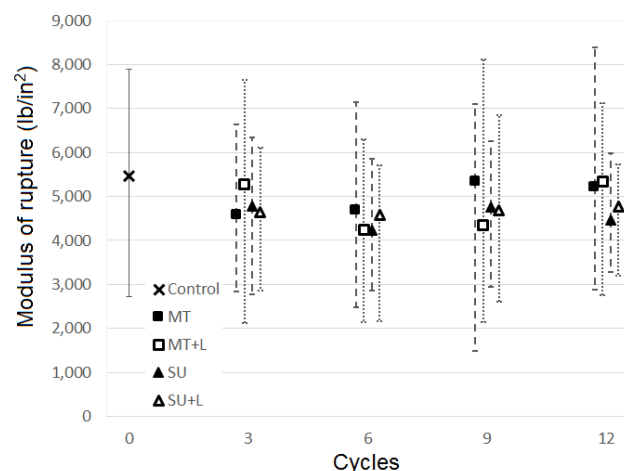


Figure 9—Modulus of rupture values of moisture-temperature (MT), moisture-temperature under load (MT+L), submersion unloaded (SU), and submersion loaded (SU+L) groups. The symbols indicate the average value for the group. The vertical bars indicate the range for the group.

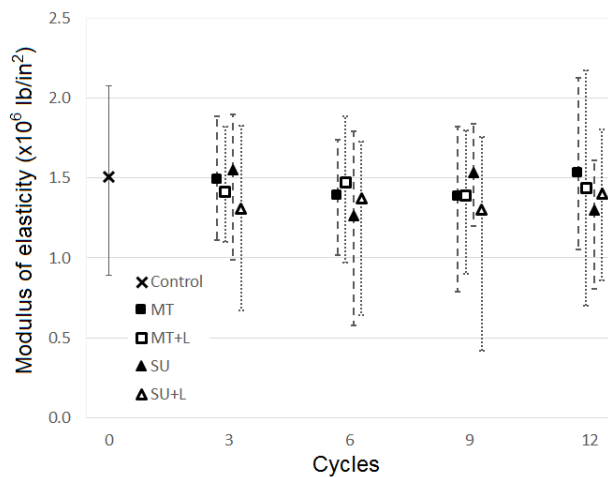


Figure 10—Modulus of elasticity values of moisture-temperature (MT), moisture-temperature under load (MT+L), submersion unloaded (SU), and submersion loaded (SU+L) groups. The symbols indicate the average value for the group. The vertical bars indicate the range for the group.

the MT groups, a 16% decrease from control, occurred in the 3-cycle group. The largest magnitude drop in average MOR for the MT+L groups, a 23% decrease from control, occurred in the 6-cycle group. All MT and MT+L average MOR values decreased with respect to the control value.

Similarly, the SU and SU+L cycles had a deleterious effect on the MOR of the plywood specimens, but a definitive trend did not appear. There was a drop in average MOR values between the control and the 3-cycle group; thereafter, the average MOR values did not consistently increase or decrease from the 3-cycle group value. The largest magnitude drop in average MOR for the SU groups, a 23% decrease from control, occurred in the 6-cycle group. The largest magnitude drop in average MOR for the SU+L groups, a 16% decrease from control, occurred in the 6-cycle group. None of the average MOR values from any of the SU or SU+L groups were higher than the control value.

The average static MOE values for MT, MT+L, SU, and SU+L groups are shown in Figure 10. The symbols and lines have the same meaning as those in Figure 9.

The average static MOE values for the MT group ranged from 8% below the control group to 2% above control. For the MT+L group, the range was 8% below to 2% below control. The range of average static MOE values for the SU and SU+L groups were larger than the MT and MT+L groups. The SU group had values ranging from 16% below to 3% above control. The SU+L group had a range of 13% below to 7% below control. No definitive trend with respect to number of cycles appeared in the MT, MT+L, SU, or SU+L groups with respect to average static MOE.

The MOR values for VSD and VSD+S groups are shown in Figure 11. The symbols and lines have the same meaning as

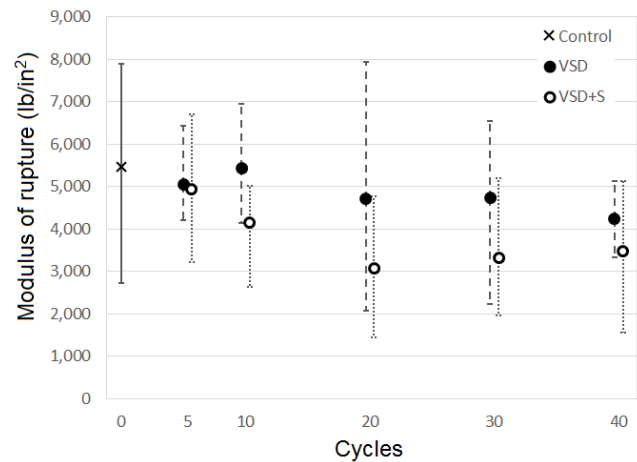


Figure 11—Modulus of rupture values of vacuum soak-oven-dry (VSD) and vacuum soak-oven-dry plus salt (VSD+S) groups. The symbols indicate the average value for the group. The vertical bars indicate the range for the group.

those in Figure 9. The VSD and VSD+S cycles had a deleterious effect on the MOR of the plywood specimens with increasing cycles. None of the average MOR values from any of the VSD or VSD+S groups were higher than the control value. There was a noticeable downward trend for the VSD+S group that continued for cycles 5, 10, and 20. At cycle 20, 30, and 40, the averages tended to have more consistent values and the downward trend was no longer present. The largest magnitude drop in average MOR for the VSD+S group, a 44% decrease from control, occurred in the 20-cycle group. An overall downward trend of MOR values was also noticeable in the VSD specimens for increasing cycles; however, the trend was not as consistent as the low-cycle VSD+S groups. The largest magnitude drop in average MOR for the VSD group, a 23% decrease from control, occurred in the 40-cycle group.

The MOE values for VSD and VSD+S groups are shown in Figure 12. The symbols and lines have the same meaning as those in Figure 9. The VSD and VSD+S cycles tended to have a deleterious effect on the MOE of the plywood specimens with increasing cycles. All of the average static MOE values decreased with respect to the control value. The trends of the MOE values mirrored those of the MOR values. There was a noticeable downward trend for the VSD+S group that continued for cycles 5, 10, and 20. The largest magnitude drop in average MOE for the VSD+S group, a 25% decrease from control, occurred in the 20-cycle group. At cycle 20, 30, and 40, the averages tended to have more consistent values and the downward trend was no longer present. An overall downward trend of MOE values was also noticeable in the VSD specimens for increasing cycles; however, the trend was not as consistent as that for the low-cycle VSD+S groups. The largest magnitude drop in average MOE for the VSD group, a 19% decrease from the control, occurred in the 40-cycle group.

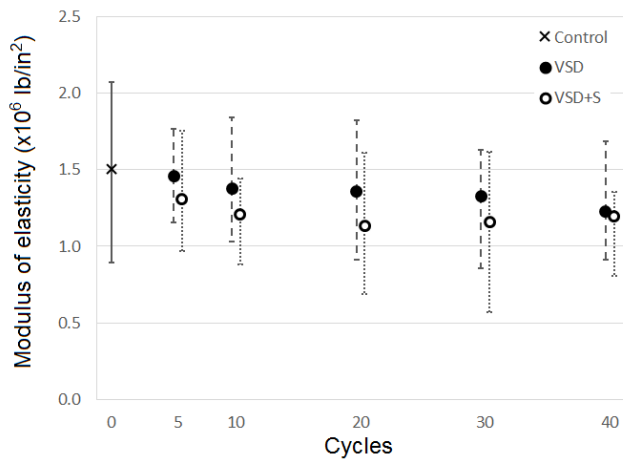


Figure 12—Modulus of elasticity values of vacuum soak-oven-dry (VSD) and vacuum soak-oven-dry plus salt (VSD+S) groups. The symbols indicate the average value for the group. The vertical bars indicate the range for the group.

3.2. Tensile–Shear Test Results

As shown in Figure 13, no trends were readily apparent for peak load values with respect to increasing number of cycles for the MT, MT+L, SU, and SU+L groups. The MT peak values ranged from 2% to 10% below the control value. The SU peak values ranged from 3% to 12% below the control value. The 3-cycle MT+L group was 8% lower than the control value, but all other MT+L values were greater than the control with the 12 cycle having the highest value at 14% above the control value. The 6-cycle SU+L group was 6% greater than the control value, but all other SU+L peak values were less than the control with the 3 cycle having the lowest value at 16% below the control value.

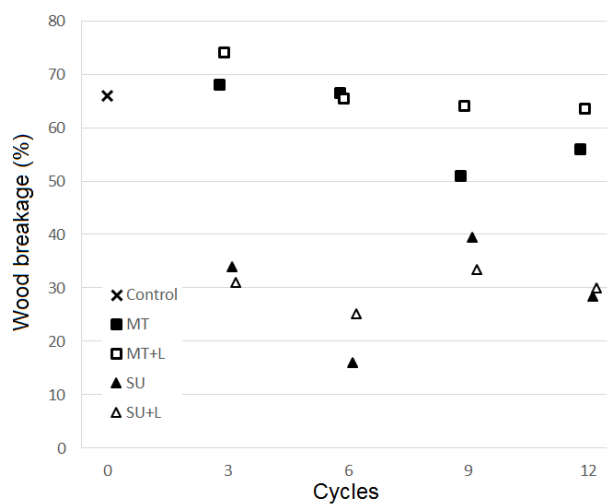


Figure 14—Percentage wood breakage during tensile-shear testing of moisture-temperature (MT), moisture-temperature under load (MT+L), submersion unloaded (SU), and submersion loaded (SU+L) groups.

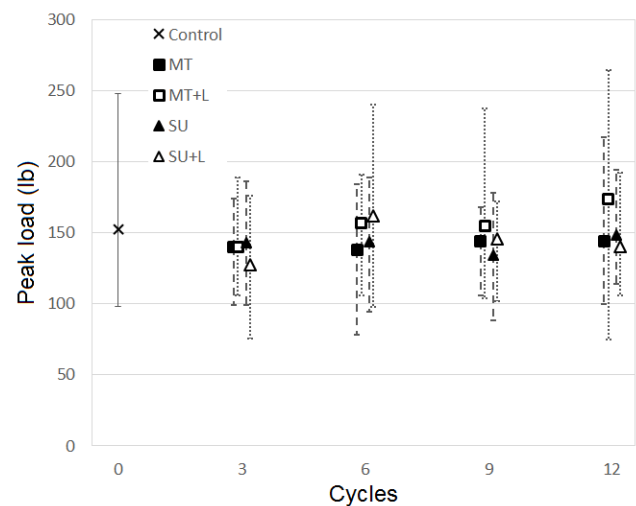


Figure 13—Peak load recorded during tensile-shear testing of moisture-temperature (MT), moisture-temperature under load (MT+L), submersion unloaded (SU), and submersion loaded (SU+L) groups. The vertical bars indicate the range for the group.

As shown in Figure 14, the average percentage wood breakage for the MT and MT+L group equaled or exceeded the control group for the 3- and 6-cycle groups of MT and MT+L. The peak values for the 9- and 12-cycle groups fell below the control. The MT+L 9- and 12-cycle groups were 2 percentage points below the control value. The MT 9- and 12-cycle groups were 15 and 10 percentage points below the control value, respectively. For both the MT and MT+L groups, there was an initial increase between the control group and the 3-cycle group, followed by a slight downward trend with respect to increasing number of cycles.

The average percentage wood breakage for the SU and SU+L group fell below the control value (Fig. 14). The highest average percentage wood breakage of the SU and SU+L groups was the 9-cycle SU, which was 26 percentage points lower than the control. All other average percentage wood breakage values for SU and SU+L were less than 30 percentage points below the control with the SU 6-cycle group being the lowest at 50 percentage points below the control.

As shown in Figure 15, the average peak loads of the VSD and VSD+S groups were lower than the average peak load of the control group for all cycle groups. For both VSD and VSD+S, a general downward trend with respect to number of cycles was apparent. With the exception of the 10-cycle groups, the average peak loads for the VSD+S groups were lower than those of the VSD groups. Within the VSD set, the 10-cycle group had the lowest average peak load value at 64% of control. The lowest value within the VSD+S set was the 30-cycle group, which was 53% of the control value.

As shown in Figure 16, there was no noticeable trend in percentage wood breakage with respect to number of cycles

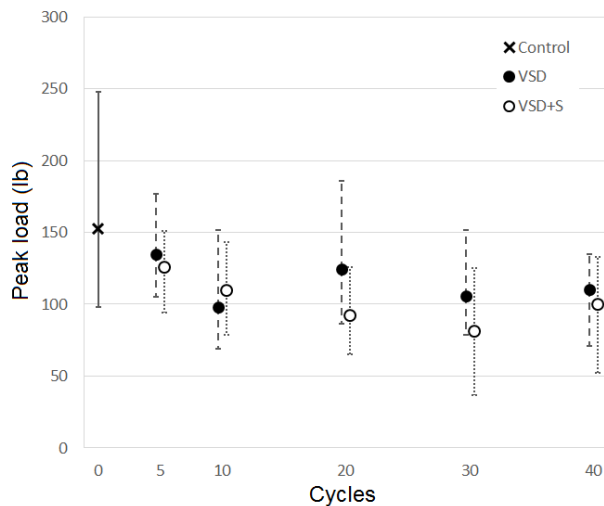


Figure 15—Peak load recorded during tensile-shear testing of vacuum soak-oven-dry (VSD) and vacuum soak-oven-dry plus salt (VSD+S) groups. The vertical bars indicate the range for the group.

for the VSD and VSD+S group. The average percentage wood breakage was below the control for all VSD and VSD+S groups. For all cycles, the values of the VSD+S groups were lower than those of the VSD groups. Large variations in percentage wood breakage per group existed from one cycle group to the next. The 10-cycle VSD group was 4 percentage points below the control, but the 20-cycle VSD group was 30 percentage points below the control. The 10-cycle VSD+S group was 5 percentage points below the control, but the 20-cycle VSD+S group was 44 percentage points below the control.

3.3. Preservative Treatment Test Results

The CCA retentions by cycle are shown in Figure 17 for the MT, MT+L, SU, and SU+L groups and in Figure 18 for the

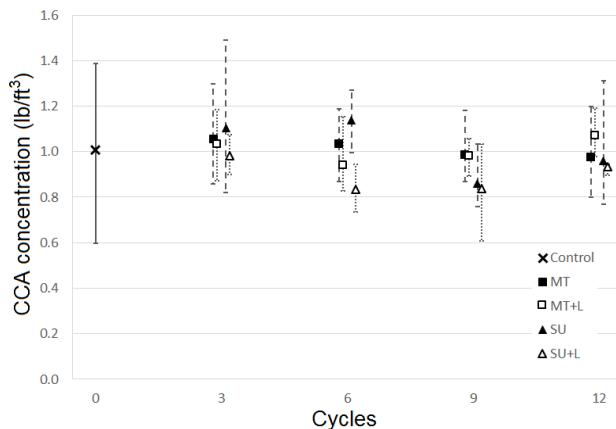


Figure 17—Chromated copper arsenate (CCA) concentration moisture-temperature (MT), moisture-temperature under load (MT+L), submersion unloaded (SU), and submersion loaded (SU+L) groups. The vertical bars indicate the range for the group.

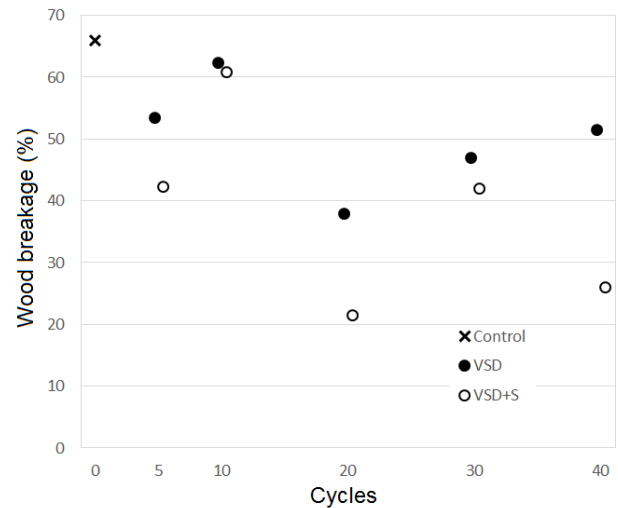


Figure 16—Percentage wood breakage during tensile shear testing for vacuum soak-oven-dry (VSD) and vacuum soak-oven-dry plus salt (VSD+S) groups.

VSD and VSD+S groups. Tables of the values can be found in Appendix B. The values presented assumed a specific gravity of 0.5 for the plywood. The CCA retention estimates are proportional to the specific gravity. After oven-drying, the average specific gravity for the test specimens was found to be 0.545 with a standard deviation of 0.035, which indicates that the CCA retention values presented in this report are likely to be conservatively low. Ten control replicates were tested, and the average CCA retention was 1.01 lb/ft³. The highest standardized CCA retention level is 0.80 lb/ft³ for use in AWP use category 4C (piles) (Lebow 2010). The fact that the control material is treated in excess of what is required for use category 4C suggests that it is unlikely that this wood will experience biodeterioration.

The 95% confidence interval of the control samples was found to be 0.89 to 1.13 lb/ft³ (calculated from standard

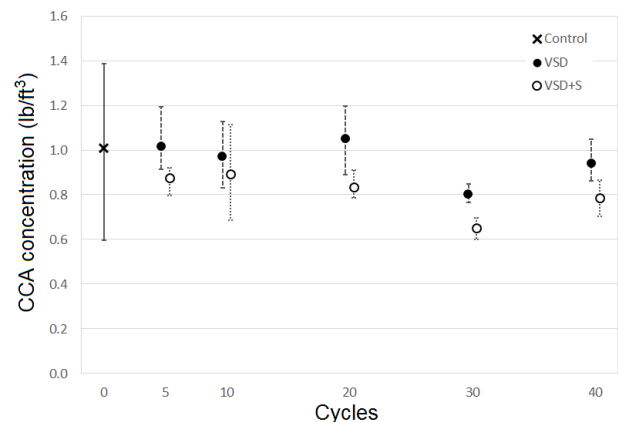


Figure 18—Chromated copper arsenate (CCA) concentration vacuum soak-oven-dry (VSD) and vacuum soak-oven-dry plus salt (VSD+S) groups. The vertical bars indicate the range for the group.

deviation 0.19 lb/ft³ on 10 replicates). In general, CCA retentions depend on the capillary uptake of the treating solution during the treatment process and are known to vary widely throughout a piece of wood and from piece to piece.

For CCA retentions of the MT, MT+L, SU, and SU+L groups, there were no trends in the data and the averages for all conditions except the 6- and 9-month SU+L and the 9-month SU fell within the 95% confidence interval of the control. Similarly for the VSD group, there were no apparent trends in the data and in most conditions (except the 30-cycle group), the average retentions fell within the 95% confidence interval of the control. However, for the VSD+S specimens, all groups subjected to 20 cycles or more fell outside of the 95% confidence interval of the control. One potential explanation is that some leaching occurred during the VSD+S process, with concentrations as low as 0.60 lb/ft³ (standard deviation 0.04 lb/ft³) after 30 cycles. Interestingly, the 40-cycle group had a higher concentration of CCA (0.79 lb/ft³).

It appears that for most of the groups, CCA retention remained within the statistical variations of the CCA retentions in the control group. For the VSD+S, there appeared to be some leaching, with average values falling outside of the 95% confidence interval of the control after 20 cycles. However, even the lowest measured retention of 0.60 lb/ft³ is still an extremely high loading of CCA and is in excess of the amount required for use category 4 for everything except piles.

4. Summary

A comprehensive study was undertaken to investigate the effects that several accelerated aging methods have on the mechanical properties of preservative-treated structural plywood. Plywood specimens were subjected to cycles of varying MC, temperature, load, and water quality. The following testing regimes were used to artificially age the specimens: MT, MT+L, VSD, VSD+S, SU, and SU+L. After aging, the specimens were tested in flexure to determine their MOE and MOR. Tensile–shear specimens obtained from the failed flexure specimens were then tested to failure.

As expected, the VSD+S aging process resulted in the largest changes in both flexural properties and tensile–shear strength. The VSD and VSD+S processes provided the most severe conditions of the three sources of degradation. The temperatures to which the specimens were exposed during the VSD and VSD+S were higher than those for the other artificial aging processes, increasing the likelihood and severity of thermal degradation. The maximum MC of the specimens of the VSD and VSD+S were higher than those of the other artificial aging processes (16.3% and below for MT and MT+L, 59% to 76% for SU and SU+L, and 86% to 111% for VSD and VSD+S), increasing the likelihood of hydrolysis degradation. The VSD and VSD+S had the largest MC change between wet and dry portions ($\Delta 5\%$ for

MT and MT+L, $\Delta 47\%$ for SU and SU+L, and $\Delta > 76\%$ for VSD and VSD+S). During the wet portion of the aging cycles, the MC crossed the fiber saturation point for the SU, SU+L, VSD, and VSD+S processes; however, during the dry portion of the cycles, the SU and SU+L did not drop below 17% and the VSD and VSD+S had MC below 10%. As a result, the shrinking and swelling stresses to which the plywood specimens undergoing the VSD and VSD+S processes would have been subjected were equal to or greater than those of the SU and SU+L. Shrinking and swelling stresses result in bond line and substrate deterioration weakening the plywood. The salt solution used in the VSD+S could provide an additional avenue for degradation by mechanical destruction of the wood cells through formation of salt crystals during the drying process, chemical breakdown of the wood in the presence of the salt solution, or both. Lastly, the VSD and VSD+S had a greater number of cycles than did the MT, MT+L, SU, and SU+L processes; however, a comparison was made between a like numbers of cycles for each aging process. The flexural strength and tensile–shear strength of the VSD+S 10-cycle group was compared with the MT, MT+L, SU, and SU+L 12-cycle groups. In each case, the average value for the VSD+S was less than the average value for any of the other artificially aged groups. The VSD+S process caused the most severe degradation of all the artificial aging processes.

Future work will include attempting to model the degrading effect of the artificial aging on the plywood. In addition, the artificial aging will be tied to real world weathering in an attempt to determine how much real world weathering time is equivalent to each cycle of the different artificial aging processes. Lastly, microscopic analysis of the VSD+S group will expand our understanding of the degradation mechanisms associated with that particular artificial aging process.

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7. Appendix A—Moisture–Temperature and Moisture–Temperature under Load Humidity Chamber Monitoring

Table A1—Temperature and percentage relative humidity of moisture–temperature cycling and moisture–temperature cycling under load humidity chamber

Cycle	Percentage relative humidity				Temperature (°F)				Dates ^a		Date ^a of weight measurement	Ending approx. moisture content (%)
	Time fraction in desired range				Time fraction in desired range							
	Avg.	Below	Within	Above	Avg.	Below	Within	Above	Start	End		
Wet 1	76.57	0.02	0.78	0.20	88.89	0.00	0.93	0.07	11/10/15	11/25/15	11/24/15	16.24
Dry 1	50.55	0.02	0.98	0.00	70.31	0.02	0.98	0.00	11/26/15	12/9/15	12/9/15	12.63
Wet 2	79.68	0.00	0.96	0.03	89.78	0.00	1.00	0.00	12/10/15	12/24/15	12/23/15	16.23
Dry 2	50.21	0.01	0.99	0.00	69.95	0.00	1.00	0.00	12/25/15	1/8/15	1/8/15	12.82
Wet 3	79.69	0.01	0.96	0.04	89.72	0.00	1.00	0.00	1/9/15	1/23/15	1/22/15	16.21
Dry 3	53.00	0.23	0.77	0.00	70.38	0.01	0.99	0.01	1/24/15	2/7/15	—	—
Wet 4	73.03	0.00	0.45	0.54	91.23	0.17	0.83	0.00	2/8/15	2/22/15	2/19/15	13.27
Dry 4	52.73	0.16	0.84	0.00	70.22	0.03	0.97	0.00	2/23/15	3/9/15	3/9/15	13.01
Wet 5	79.91	0.03	0.90	0.07	89.76	0.00	1.00	0.00	3/10/15	3/24/15	3/24/15	15.92
Dry 5	53.76	0.42	0.58	0.00	69.98	0.00	1.00	0.00	3/25/15	4/8/15	4/7/15	13.08
Wet 6	78.17	0.11	0.59	0.30	89.79	0.00	1.00	0.00	4/9/15	4/23/15	4/23/15	15.45
Dry 6	56.23	0.63	0.37	0.00	69.99	0.00	1.00	0.00	4/24/15	5/8/15	5/8/15	13.59
Wet 7	77.30	0.08	0.46	0.46	89.78	0.00	1.00	0.00	5/9/15	5/23/15	5/21/15	15.50
Dry 7	59.15	0.84	0.16	0.00	70.02	0.00	1.00	0.00	5/24/15	6/7/15	6/4/15	13.79
Wet 8	79.85	0.02	0.95	0.03	89.81	0.00	0.99	0.00	6/8/15	6/22/15	6/22/15	15.82
Dry 8	54.97	0.61	0.37	0.02	69.99	0.00	1.00	0.00	6/23/15	7/7/15	7/7/15	13.30
Wet 9	71.57	0.02	0.36	0.62	89.35	0.00	0.99	0.01	7/8/15	7/22/15	7/22/15	15.14
Dry 9	55.56	0.71	0.29	0.00	69.99	0.00	1.00	0.00	7/23/15	8/6/15	8/6/15	13.40
Wet 10	80.00	0.03	0.91	0.06	89.76	0.00	1.00	0.00	8/7/15	8/21/15	8/21/15	15.74
Dry 10	49.96	0.17	0.56	0.26	70.15	0.00	1.00	0.00	8/22/15	9/5/15	9/3/15	11.91
Wet 11	71.14	0.04	0.60	0.36	89.75	0.00	1.00	0.00	9/6/15	9/20/15	9/17/15	15.46
Dry 11	46.74	0.04	0.69	0.27	70.00	0.00	1.00	0.00	9/21/15	10/5/15	10/5/15	11.53
Wet 12	75.35	0.09	0.35	0.56	89.81	0.00	1.00	0.00	10/6/15	10/20/15	10/20/15	14.86
Dry 12	46.62	0.56	0.34	0.09	70.45	0.58	0.42	0.00	10/21/15	11/9/15	11/9/15	11.78

^aMonth/day/year.

8. Appendix B—Data Tables

Table B1—Modulus of rupture (MOR) and modulus of elasticity (MOE) of moisture–temperature cycling (MT) and moisture–temperature cycling under load (MT+L) groups by cycle (SD, standard deviation; COV, coefficient of variation)

Property	Value	Control	MT cycles				MT+L cycles			
			3	6	9	12	3	6	9	12
MOR (lb/in ²)	Average	5468	4569	4680	5346	5222	5279	4231	4354	5329
	SD	1314	1284	1249	1433	1456	1634	1221	1580	1239
	COV	0.24	0.28	0.27	0.27	0.28	0.31	0.29	0.36	0.23
MOE dynamic ($\times 10^6$ lb/in ²)	Average	1.33	1.35	1.35	1.36	1.36	1.35	1.36	1.36	1.34
	SD	0.28	0.34	0.35	0.36	0.36	0.34	0.35	0.36	0.35
	COV	0.21	0.25	0.26	0.27	0.26	0.25	0.26	0.27	0.26
MOE static ($\times 10^6$ lb/in ²)	Average	1.50	1.49	1.39	1.38	1.53	1.42	1.47	1.39	1.44
	SD	0.29	0.20	0.21	0.28	0.31	0.25	0.26	0.25	0.33
	COV	0.19	0.14	0.15	0.20	0.20	0.18	0.17	0.18	0.23

Table B2—Modulus of rupture (MOR) and modulus of elasticity (MOE) of submerged unloaded (SU) and submerged loaded (SU+L) groups by cycle (SD, standard deviation; COV, coefficient of variation)

Property	Value	Control	SU cycles				SU+L cycles			
			3	6	9	12	3	6	9	12
MOR (lb/in ²)	Average	5468	4772	4231	4751	4453	4638	4584	4683	4777
	SD	1314	927	875	929	741	1065	855	1363	741
	COV	0.24	0.19	0.21	0.20	0.17	0.23	0.19	0.29	0.16
MOE dynamic ($\times 10^6$ lb/in ²)	Average	1.33	1.32	1.32	1.33	1.32	1.32	1.33	1.32	1.32
	SD	0.28	0.23	0.23	0.21	0.20	0.23	0.23	0.21	0.20
	COV	0.21	0.17	0.17	0.16	0.15	0.17	0.17	0.16	0.15
MOE static ($\times 10^6$ lb/in ²)	Average	1.50	1.55	1.27	1.53	1.30	1.31	1.37	1.30	1.40
	SD	0.29	0.27	0.38	0.18	0.22	0.40	0.30	0.35	0.30
	COV	0.19	0.17	0.30	0.12	0.17	0.31	0.22	0.27	0.22

Table B3—Modulus of rupture (MOR) and modulus of elasticity (MOE) of vacuum soak–oven-dry (VSD) and vacuum soak–oven-dry plus salt (VSD+S) groups by cycle (SD, standard deviation; COV, coefficient of variation)

Property	Value	Control	VSD cycles					VSD+S cycles				
			5	10	20	30	40	5	10	20	30	40
MOR (lb/in ²)	Average	5468	5047	5429	4702	4724	4235	4930	4139	3065	3306	3469
	SD	1314	639	1088	1745	1287	666	920	782	1040	1118	1015
	COV	0.24	0.13	0.20	0.37	0.27	0.16	0.19	0.19	0.34	0.34	0.29
MOE dynamic (×10 ⁶ lb/in ²)	Average	1.33	1.37	1.36	1.37	1.38	1.38	1.35	1.35	1.3494	1.35	1.37
	SD	0.28	0.35	0.35	0.36	0.39	0.41	0.35	0.35	0.3527	0.36	0.40
	COV	0.21	0.26	0.26	0.26	0.28	0.30	0.26	0.26	0.2614	0.26	0.29
MOE static (×10 ⁶ lb/in ²)	Average	1.50	1.46	1.38	1.36	1.33	1.23	1.31	1.21	1.131	1.16	1.20
	SD	0.29	0.22	0.27	0.32	0.26	0.24	0.24	0.18	0.287	0.36	0.17
	COV	0.19	0.15	0.19	0.24	0.19	0.19	0.18	0.15	0.2537	0.31	0.14

Table B4—Tension–shear peak load and percentage wood breakage of moisture–temperature cycling (MT) and moisture–temperature cycling under load (MT+L) groups by cycle (SD, standard deviation; COV, coefficient of variation)

Property	Value	Control	MT cycles				MT+L cycles			
			3	6	9	12	3	6	9	12
Peak load (lb)	Average	152	140	138	144	144	140	157	155	174
	SD	35.3	26.1	31.9	20.6	36.6	24.3	25.7	38.9	53.3
	COV	0.232	0.187	0.232	0.143	0.254	0.174	0.164	0.252	0.307
Percentage wood breakage	Average	66	68	66	51	56	74	66	64	64
	SD	30	34	34	17	30	25	32	26	24
	COV	0.45	0.49	0.51	0.33	0.54	0.33	0.49	0.41	0.37

Table B5—Tension–shear peak load and percentage wood breakage of vacuum soak–oven-dry (VSD) and vacuum soak–oven-dry plus salt (VSD+S) groups by cycle (SD, standard deviation; COV, coefficient of variation)

Property	Value	Control	VSD cycles					VSD+S cycles				
			5	10	20	30	40	5	10	20	30	40
Peak load (lb)	Average	152	135	97.7	125	105	111	126	109.5	93	81	100
	SD	35.3	18.5	25.7	27.7	19.5	21.6	15.8	18.7	21.6	24.9	23.2
	COV	0.232	0.138	0.263	0.222	0.184	0.195	0.125	0.171	0.234	0.307	0.233
Percentage wood breakage	Average	66	54	62	38	47	52	42	61	22	42	26
	SD	30	24	36	27	26	32	27	32	21	33	21
	COV	0.45	0.44	0.58	0.71	0.56	0.63	0.63	0.52	0.99	0.79	0.80

Table B6—Tension–shear peak load and percentage wood breakage of submerged unloaded (SU) and submerged loaded (SU+L) groups by cycle (SD, standard deviation; COV, coefficient of variation)

Property	Value	Control	SU cycles				SU+L cycles			
			3	6	9	12	3	6	9	12
Peak load (lb)	Average	152	143	144	134	148	128	161	146	140
	SD	35.3	33.4	34.3	28.3	31.1	32.4	51.1	25.2	27.0
	COV	0.232	0.23	0.24	0.21	0.21	0.25	0.32	0.17	0.19
Percentage wood breakage	Average	66	34	16	40	29	31	25	34	30
	SD	30	19	16	31	23	35	29	28	27
	COV	0.45	0.56	1.00	0.78	0.80	1.13	1.17	0.85	0.91

Table B7—Chromated copper arsenate (CCA) retention by cycle for moisture–temperature cycling (MT), moisture–temperature cycling under load (MT+L), submerged unloaded (SU), and submerged loaded (SU+L) groups

Specimen group	CCA retention (lb/ft ³)				
	0 cycles	3 cycles	6 cycles	9 cycles	12 cycles
MT	1.01	1.06	1.03	0.99	0.98
MT+L	1.01	1.03	0.94	0.98	1.07
SU	1.01	1.10	1.14	0.86	0.96
SU+L	1.01	0.98	0.84	0.84	0.93

Table B8—Average chromated copper arsenate (CCA) retention by cycle for the vacuum soak–oven-dry (VSD) and vacuum soak–oven-dry plus salt (VSD+S) groups

Specimen group	CCA retention (lb/ft ³)					
	0 cycles	5 cycles	10 cycles	20 cycles	30 cycles	40 cycles
VSD	1.01	0.99	0.88	1.05	0.80	0.94
VSD+S	1.01	0.87	0.89	0.84	0.65	0.79