Paint Adhesion to Weathered Wood

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Short-term outdoor exposure of western redcedar (WRC, *Thuja plicata)* prior to painting drastically decreased adhesion of primers. Freshly planed and unpainted WRC boards were exposed outdoors vertically facing south near Madison, WI, for 1, 2, 4, 8, or 16 weeks during the late spring and summer of 1984. Following this weathering, the boards were painted with alkyd-oil or acrylic latex primers and, after curing for three months, tested in shear or tension to determine paint adhesion. Specimens weathered for more than four weeks before painting failed primarily at the wood/paint interface while those weathered for four weeks failed either at the wood/paint interface or cohesively in the wood. The unweathered controls and boards weathered for two weeks or less failed primarily in the wood. The mean tensile strength of the paint/wood bond dropped 50% from approximately 300 psi (2,070 kPa) on wood weathered for four weeks to 150 psi (1,035 kPa) on wood weathered for 16 weeks. Shear strength dropped 33% from approximately 750 psi (5,170 kPa) to 500 psi (3,450 kPa) after similar weathering periods. The primer/wood bond strength of specimens weathered for two weeks or less is higher than the wood strength; therefore, the 50% decrease in tensile and 33% decrease in shear strengths indicate only part of the loss in paint adhesion.

INTRODUCTION

In the absence of adhesion failure, paint on wood exposed outdoors gradually erodes. Degradation of paint by this mechanism may take several years, depending on the degree of exposure to sunlight and moisture and the thickness and type of paint. During the time that a paint system is eroding, it still protects the wood surface. Until this erosion proceeds to the point where the primer begins to show, the paint surface can be repainted readily with a topcoat. With timely refinishing, painted wood can last for centuries.[1] Many homes built in the 1700's (for example, Mt. Vernon, and John Adams' home). have been painted on their original siding.

If, however, the paint/wood interface fails, the paint film will debond within a short time and the paint will blister, crack, and peel. This failure can result in damage to the wood surface and more difficult and costly refinishing. One cause of interface failure is a degraded wood surface caused by weathering prior to initial priming with paint.[2-8] These previous studies have shown in a qualitative way that long-term weathering of wood prior to painting reduces subsequent paint performance. However, no one has quantitatively related short-term weathering of wood to paint performance via paint adhesion or other measurements.

The objective of this study was to measure quantitatively the loss of primer paint adhesion to boards weathered before painting. Outdoor exposure was for relatively short periods in the late spring and summer months and ranged from 1-16 weeks. This exposure would be typical of the weathering wood siding might get during new construction. Adhesion was determined by tensile and shear tests similar to those used for testing wood-adhesive bonds. Measurement of paint adhesion may be a useful diagnostic tool for predicting the performance of paint systems applied to wood and wood-based composites. The decrease in paint adhesion to weathered wood reported here will be correlated with paint performance on wood panels that are currently being exposed outdoors. The long-range objective is to relate paint adhesion to paint and finish performance.

An alkyd-oil primer and an acrylic latex primer were used in these studies.

EXPERIMENTAL

These experiments were based on a three-way factorial design. The factors were paint type (alkyd-oil or acrylic latex), test mode (tension or shear). and exterior weathering exposure (expressed as hours of total sunlight).

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Freshly planed vertical-grained western redcedar (WRC, *Thuju plicata* Donn) boards 16×4× ⅜ in. (410, 100, and 10 mm) (longitudinal, radial, and tangential) were exposed outdoors, oriented vertically facing south near Madison, WI, in 1984 for 1, 2, 4, 8, or 16 weeks. Two samples, cut from different large boards, were exposed during each period. There were four 1-, 2-, and 4-week exposure periods, two 8-week exposure periods, and one 16-week exposure period *(Figure* 1). At the same time, four controls, also cut from the same two larger boards. were kept from exposure to sunlight in a darkened room at 27°C and 65% relative humidity (RH) for 16 weeks. When not outdoors, all specimens were kept in the darkened room.

Weathering was begun on May 1, 1984, and specimens were exposed according to the schedule in *Figure 1.* This schedule was chosen to determine the effects of weathering over extended exposure times and in a spring vs summer climate. For example, panels were exposed for one week beginning on May 1, May 29, June 26, and July 24 and received 38, 78, 81, and 65 hours of sunshine, respectively (Figure l). The hours of sunshine for the Madison area for each period were obtained from the National Oceanic and Atmospheric Administration and used for all calculations and comparisons. For convenience in the text, all exposures are referred to in weeks because, as discussed later, statistical analysis indicated no difference for the same exposure periods for the four different months.

Following weathering, the WRC boards were lightly washed with distilled water, air dried, and painted by brush with primer. One half of each board was painted

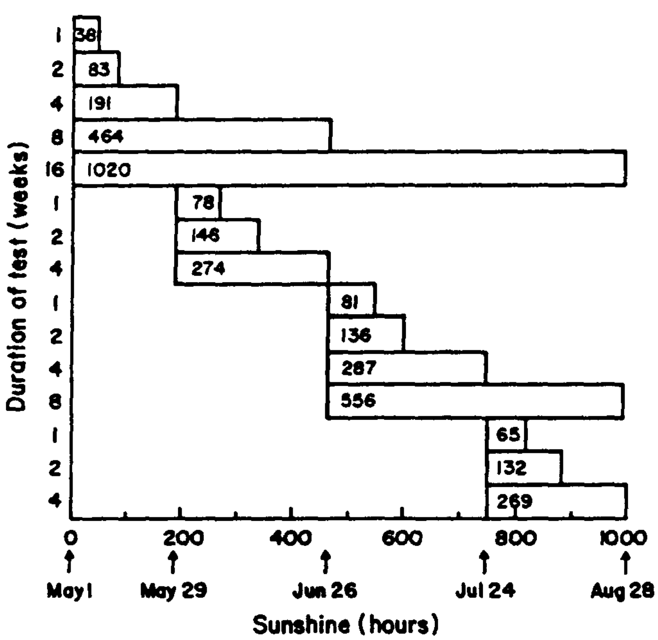

Figure 1— Hours of sunshine for the 1-,2-,4 -,8-, and 16-week uncoated specimens. The various acts of panels are defined by the vertical axis and were initiated at four different times as shown on the horizontal axis. The hours of sunshine appear in each bar. (ML86 5256)

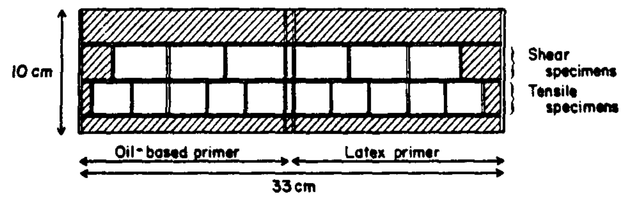

Figure 2—Top view of exposure panel showing layout of shear and tensile specimens. Crosshatched area was waste. (ML86 5257)

with alkyd-oil primer (Sherwin-Williams A- 100 Primer*) and the other half with acrylic latex primer (Du Pont Lucite Wood Primer). After the paint cured for three months, freshly planed hard maple *(Acer saccharum)* boards were glued to the painted surfaces using an emulsion polymer/isocyanate (EPI) adhesive (Ashland lsoset WD2-A312 with 10% lsoset CX-11 catalyst). The EPI adhesive contained no organic solvents that might affect the primers. The resulting panels were cured in a press at 75 psi (520 kPa) at room temperature for 36 hours. Tensile specimens and block shear specimens *(Figure 2)* were cut from each assembled WRC/maple panel after the adhesive cured. Both had 1 × 1-in. (25 × 25 mm) bond areas. The tensile specimens were then glued to aluminum blocks *(Figure* 3) using an epoxy/polyamide (Epon 828/V-40) adhesive and cured 48 hours at room temperature.

Expanded cross-sections of both the tensile and the shear specimens *(Figure* 3) show several interfaces: wood/paint, paint/EPI, and EPI/maple. In addition, the final tensile specimens had wood/epoxy and epoxy/aluminum interfaces. Hard maple. being a stronger wood, shifted the failure toward the weaker WRC/paint interface or to the WRC. The shear specimen was a further-modified version of the specimens as described in ASTM D 905[9] and modified by Strickler. [10]

Tensile specimens were subsequently equilibrated to 12% equilibrium moisture content (EMC) and tested using an lnstron test machine and a constant-displacement load rate of 1 mm/min. Shear specimens were also equilibrated to 12% EMC and tested using a constant-displacemen(load rate of 0.38 mm/min. Load and deflection readings were acquired during each tensile or shear test. Ultimate stress and the elastic stress-strain modulus were calculated from these values.

Failure of the paint/EPI. EPI/maple, wood/epoxy, or epoxy/aluminum interfaces was deemed unacceptable because only failures of the weathered wood substrate or of the WRC/paint interface were considered pertinent. Accordingly, all specimens were visually examined for failure site following testing and only those exhibiting the specified failure type were used to compare adhesion.

RESULTS

Many specimens weathered less than four weeks before painting failed primarily within the WRC substrate,

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yielding little useful adhesion information other than that the paint/wood interface was stronger than the wood substrate. These substrate failures occurred totally within the wood and are attributed to cohesive failure in the wood and not to weathering. For specimens weathered for four weeks. approximately 50% of the specimens failed at the paint/wood interface and 50% failed cohesively in the wood substrate. However, for specimens weathered for eight or 16 weeks, failure occurred almost exclusively at the paint/wood interface. This interface includes both the weathered wood surface and the portion of the paint film in contact with the surface. A plot of all failures in the tensile tests of latex primer is shown in *Figure* 4. This graph is typical of the data for the other tests as outlined in the sections below.

This study was designed to determine if the time of year for the one- to eight-week exposure periods had a significant effect. Most of the tests on one- and two-week specimens resulted in wood failure and showed no differences among the various exposure periods or the time of year. Also, the results from longer exposure periods could not be correlated with either the time of year or the amount of sun exposure during these periods *(Figure* 1).

Latex Primer

TENSILE TESTS: As discussed, tensile tests of specimens painted with latex primer exhibited both primer/wood interface and wood failure. The failures were predominately cohesive wood failure or total interface failure; there was little partial wood/partial interface failure except for the four-week specimens *(Figure* 5). The two halves of the tensile specimens are shown for two representative 2-, 4-, 8-, and 16-week specimens. Only the substrate half is shown for the controls and one-week specimens because all failures occurred in the WRC. Note the change from total wood failure in the controls and one-week specimens to total primer failure in the 16-week specimens. This wood failure occurred away from the interface at a depth of 2 to 3 mm and therefore was not caused by weathering because sunlight penetrates the wood surface only about 75 µm.[11]

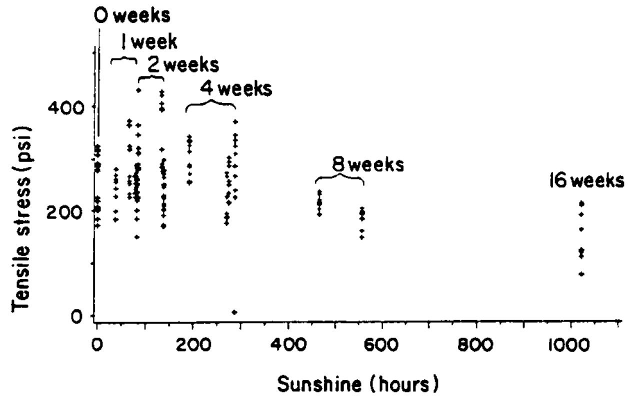

Figure 4— Ultimate tensile stress (psi) vs sunlight exposure time of acrylic latex primer on WRC. All adhesive failures and cohesive wood failures are shown. (ML86 5259)

A Duncan Multiple Range Test of Means[12] showed no difference between controls and specimens exposed for 1, 2, and 4 weeks. The distribution in tensile strengths from zero to four weeks *(Figure* 4) is probably attributable to wood variation, not paint adhesion. Mean tensile strength remains constant for up to four weeks. then as interface failure becomes the dominant failure mode, it begins to decline. This trend can be more easily seen when specimens that failed totally in the wood are deleted *(Figure 6).* The mean tensile strength of the wood/latex primer bond decreased from 310 psi (2,125 kPa) after weathering for four weeks to 150 psi (1,040 kPa) after weathering for 16 weeks *(Table* 1).

SHEAR TESTS: In the shear test, there was little wood substrate failure as failures occurred primarily at the latex primer/wood interface with essentially 100% primer adhesion failure on the eight- and 16-week specimens *(Figure* 7). The shear results were similar to the tensile results and showed no significant differences in mean shear strengths of 800, 765, and 750 psi (5,505, 5,260, and 5,150 kPa), respectively, for specimens exposed for 0.1, or 2 weeks. The four-week specimens were statistically different than the controls but not the one- and two-week specimens *(Table* 1). The decrease in adhesion after four weeks of exposure is evident in *Figure 8.* The reduction in strength from 800 psi (5,505 kPa), for the controls, to 450 psi (3,095 kPa) after 16 weeks was not as great as with the tensile values *(Table* 1). however, the trend was the same. As with the tensile tests, failure at the primer/EPI and/or the EPI/maple interfaces were ignored and

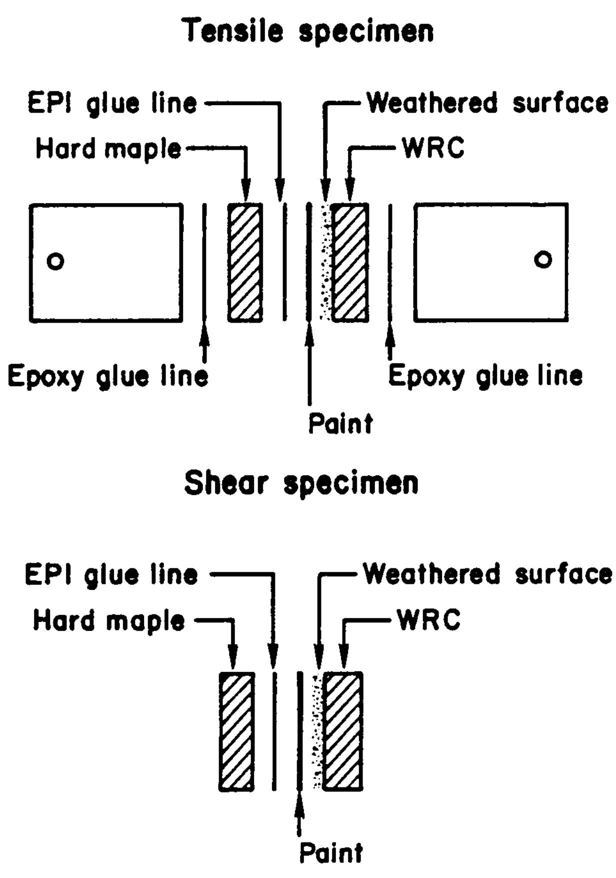

Figure 3—Expanded view of tensile and shear specimens showing interfaces. (ML86 5258)

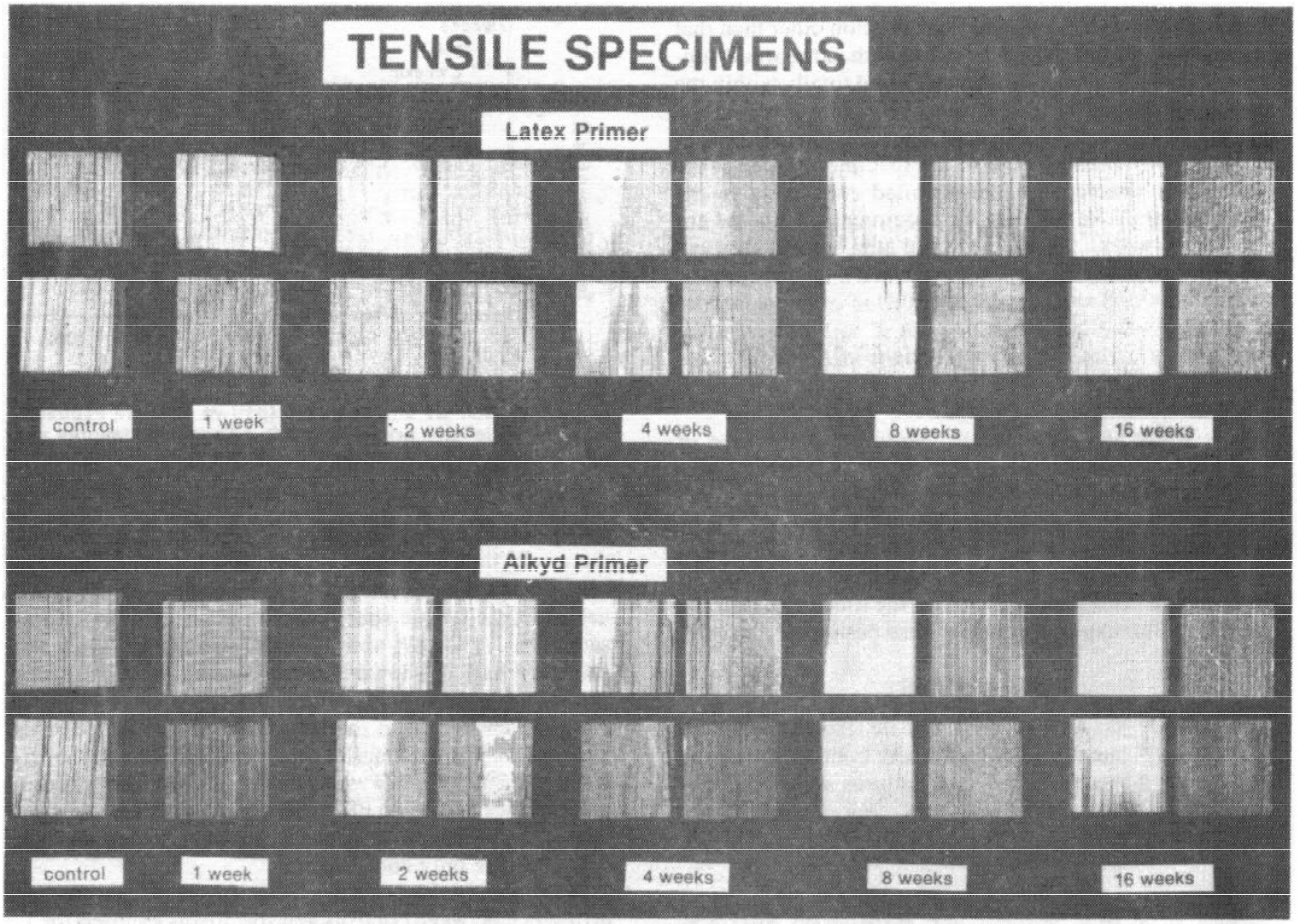

Figure 5—Failure surfaces of representative tensile specimens. (M86 0043)

only the results from specimens that failed at the wood/primer interface were analyzed.

Alkyd-Oil Primer

TENSILE TESTS: The mean tensile strength of the oil primer on wood weathered four weeks before painting was 255 psi (1,765 kPa) compared to 125 psi (870 kPa)

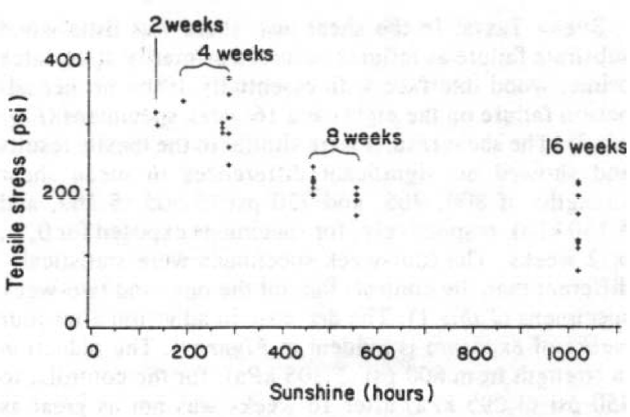

Figure 6—Ultimate tensile stress (psi) vs sunlight exposure time of acrylic latex primer on WRC. Only primer/wood interface failures are shown. (ML86 5260)

after 16 weeks of weathering (*Table* 1, *Figure* 9). As with the latex primer, ultimate strength for many specimens weathered two weeks or less reflected only wood failure and were deleted. The failure mechanism for the oil primer is more complicated than for the latex primer because adhesion of paint to latewood (summerwood) is better than to earlywood (springwood) (*Figure* 5). This failure of the earlywood/paint interface rather than the latewood/paint interface is opposite to the expected failure site and is considered in detail in the Discussion section.

SHEAR TESTS: The change in shear strength of oil primer with time (*Figure* 10) shows the same trend as the tensile results. The mean adhesion strength dropped from 700 to 490 psi (4,815 to 3,380 kPa) (*Table* 1). As observed in the tensile tests, better adhesion of the oil primer to weathered latewood was observed for the shear specimens (*Figure* 7). As with the shear tests on the latex primers, only a few values were discarded because failure occurred other than at the interface region.

DISCUSSION

The mean tensile and shear strength at failure for both paints are listed in *Table* 1. Using a linear model,

$$\text{Load} = b_0 + b_1 \text{ (weathering exposure tim}$$

Table 1—Results of a Duncan Multiple Range Test on the Mean Adhesive Strength of Wood/Primer at Alpha = 0.05[a]

LATEX PRIMER

	Tensile Test (R^2 = 0.782)						Shear Test (R^2 = 0.591)					
Number[b]	0	0	2	10	15	10	24	11	24	24	12	6
Exposure (wk)	0	1	2	4	8	16	0	1	2	4	8	16
Strength (psi)	—	—	310	305	200	150	800	765	750	710	560	450
Strength (kPa)	—	—	2.125	2.090	1.370	1.040	5.500	5.260	5.150	4.875	3.875	3.095

ALKYD-OIL PRIMER

	Tensile Test (R^2 = 0.579)						Shear Test (R^2 = 0.455)					
Number[b]	0	0	19	14	18	6	7	0	15	22	12	6
Exposure (wk)	0	1	2	4	8	16	0	1	2	4	8	16
Strength (psi)	—	—	190	255	155	125	690	—	700	675	530	490
Strength (kPa)	—	—	1.305	1.765	1.055	870	4.745	—	4.815	4.645	3.655	3.380

(a) The breaks in the bar shown under the strength values represents a significant difference between those at a means with 95% of confidence.
(b) Number of specimens failing at the wood/paint interface.

a Duncan's Multiple Range Test of Means shows significant (alpha =0.05) loss of adhesion for all groups after four weeks of weathering. An α value of 0.05 indicates 95% confidence that there is a significant difference between two means. This is shown by the breaks in the underlines in *Table* 1. Load-deflection curves were plotted for all tests. Latex primer exhibited a greater overall deflection prior to failure, lower modulus of elasticity, and higher adhesive strength than for the oil primer. This probably relates more to physical differences between the two paints than to weathering effects.

With both paints, the differences in the elastic modulus of earlywood/latewood bands in wood may set up stress concentrations at the junction of these bands. The flexible

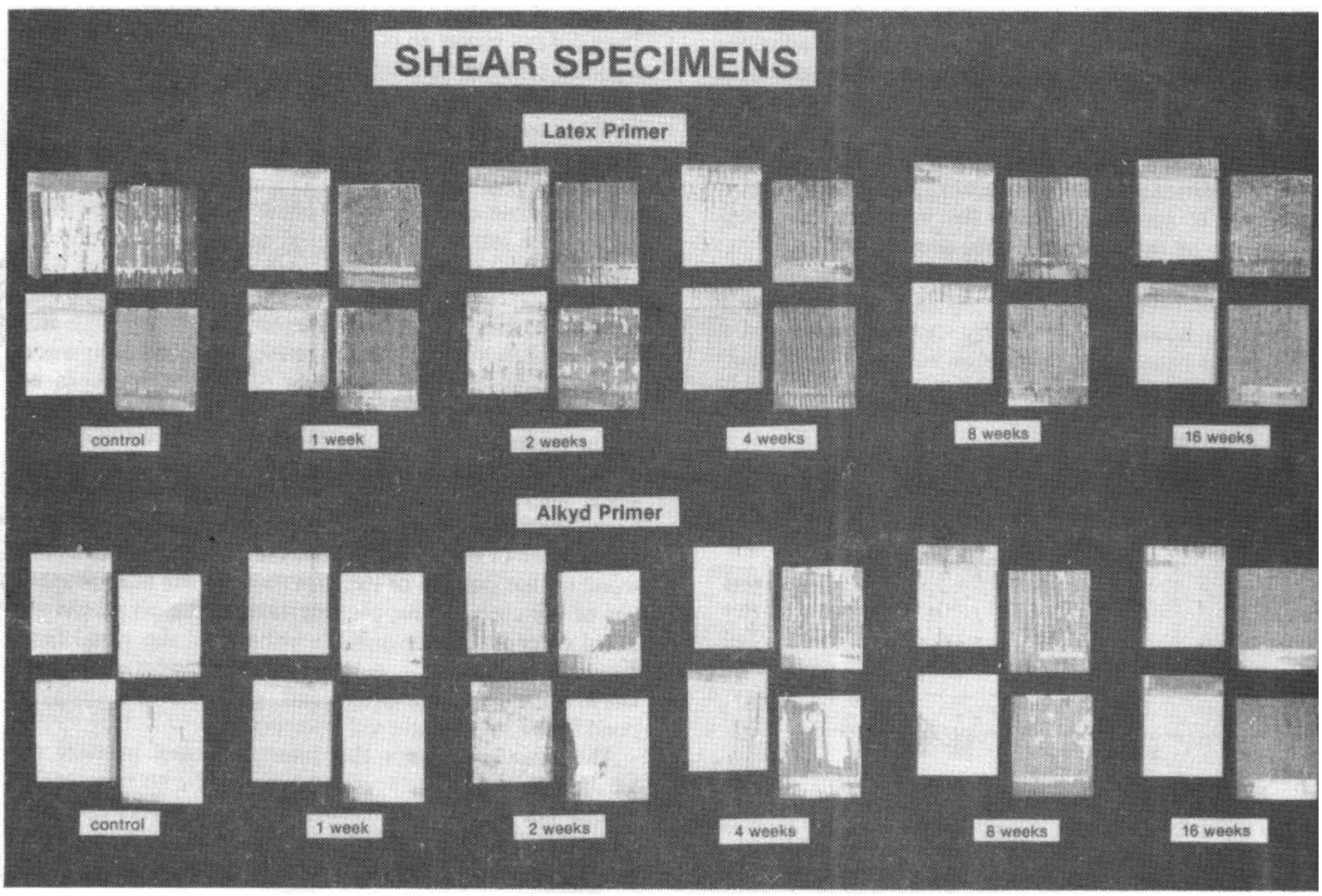

Figure 7—Failure surfaces of representative shear specimens. (M86 0046)

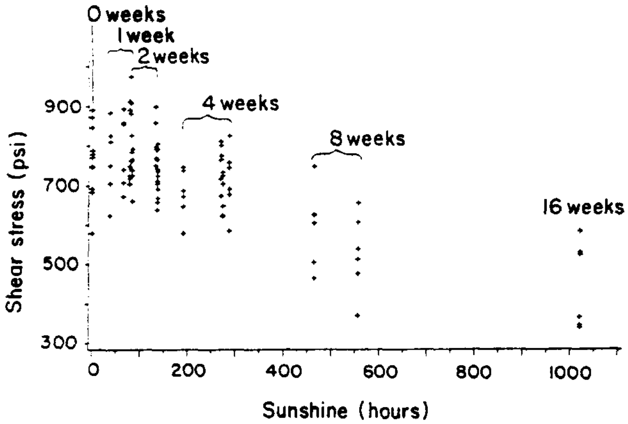

Figure 8—Ultimate shear stress (psi) vs sunlight exposure time of acrylic latex primer on WRC. Only primer/wood interface failures are shown. (ML86 5261)

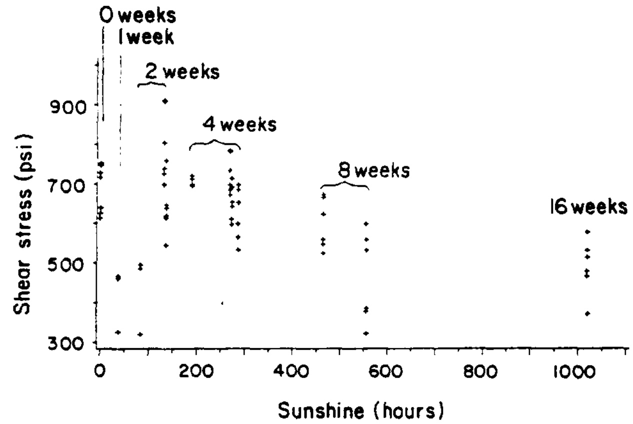

Figure 10—Ultimate shear stress (psi) vs sunlight exposure time of alkyd-oil primer on WRC. Only primer/wood interface failures are shown. (ML86 5263)

latex primer film may more easily absorb this differential strain energy without failing. The less flexible oil primer cracks at lower strain energy levels along the earlywood/latewood boundaries, failing at lower loads. Both tensile and shear specimens showed this break at the earlywood/latewood boundary *(Figures* 5 and 7). This type of crack formation of oil primer at the earlywood/latewood boundary has previously been reported and was caused by increased wood moisture content.[13, 14] Differences in earlywood and latewood primer adhesion of the oil primer may be related to failure at this boundary. The change in adhesive strength with weathering was less for the alkyd-oil primer. This may be caused by the higher adhesive strength to the latewood. However, as mentioned above, the greater adhesion of the oil primer to latewood was unusual because it is fairly well accepted that paint in contrast to clear finishes, adheres better to earlywood.

This traditional view of better paint adhesion to earlywood is appropriate only for unweathered wood. The results of these experiments showed no difference between earlywood and latewood adhesion for the controls and one-week specimens. After a short period of weathering, however, the damage to the earlywood is sufficient to cause paint failure on this part of the substrate. While only a few of the two-week weathered specimens failed at the earlywood/paint interface, this apparent anomaly became the general failure site in the specimens weathered 4, 8, and 16 weeks before painting *(Figures* 5 and 7). The differential failure of the oil primer on earlywood/latewood and the uniform failure of the latex paint may be explained by the difference in the interface formed by these different paints with the weathered wood surface:

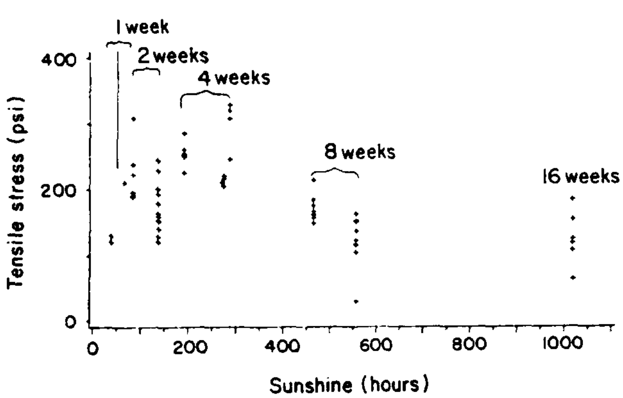

Figure 9— Ultimate tensile stress (psi) vs sunlight exposure time of alkyd-oil primer on WRC. Only primer/wood interface failures are shown. (ML86 5262)

Hon and Ifju[11] reported that penetration of light into wood is a function of wavelength and the ultraviolet (UV) portion of sunlight penetrates approximately 75 µm. They did not report an effect caused by wood density, but reported on both tangential and radial sections of WRC, redwood *[Sequoia sempervirens* (D. Don) Endl.]. Douglas-fir *[Pseudotsuga menziesii* (Mirb.) Endl.]. and southern pine *(Pinus* spp.). We reviewed their results and concluded that less UV light is transmitted through the radial sections containing the more dense latewood than through the less dense tangential earlywood sections. In view of the faster erosion of earlywood compared with latewood,[1,15,16] it appears reasonable to conclude that the degradation of the earlywood occurs to a greater depth. The failure of the oil primer over the earlywood sections may be related to this difference in depth of degradation

The molecular size of the modified oils used in the oil primer may be small enough for some penetration into the wood microstructure (cell wall).[17] If the interface between the paint and the wood is considered to extend from that portion of the wood that has the bulk properties of the wood to that portion of the film that has the bulk properties of the cured paint. the interface of the oil primer on wood extends farther into the volume of the wood than the latex. primer. Since the subsurface degradation of latewood is less than earlywood. paint forms a stronger bond in the less weathered latewood.

The situation is not the same for latex primers on weathered wood. The specimens painted with latex primer did not show a difference between earlywood and latewood. The micelles of polymer resins in latexes are too large to penetrate the wood microstructure (cell wall),[17,18] therefore differences in depth of degradation for earlywood and latewood should not affect adhesion of the latex primer.

CONCLUSIONS

Adhesion of both an acrylic latex and an alkyd-oil primer to wood is significantly reduced after the wood substrate has weathered for four or more weeks before painting. These results were observed when evaluating exterior wood finishes in southern Wisconsin. A greater effect in warmer and, especially. sunnier climates could be anticipated.

Reduced paint adhesion and increased wood/paint interface failure will undoubtedly result in poor long-term paint and finish performance on wood specimens weathered four or more weeks before finishing. Because of this, it is strongly recommended that any unprotected wood not be allowed to weather outdoors for more than two weeks before it is protected with some finish that will prevent photodegradation and water damage. This recommendation is based on the observation that there was almost no wood/paint interface failure observed in wood specimens that were weathered for two weeks or less.

We are currently conducting long-term outdoor exposure studies on paint and other finishes on weathered western redcedar boards and Douglas-fir roughsawn plywood. The results of these long-term exposure studies will be described in future publications.

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References

(1) Feist, W.C. and Hon, D.N.-S., "Chemistry of Weathering and Protection," in Chemistry of Solid Wood, *Advances in Chemistry Series*, ed. by R.M. Rowell. American Chemical Society, 1984, p. 401-451.

(2) Underhaug, Å., Lund, T.J., and Kleive, K., "Wood Protection—The Interaction Between Substrate and the Influence on Durability," *J. Oil & Colour Chemists' Assoc.*, *66* (11), 345 (1983).

(3) Miller, E.R., "Chemical Aspects of External Coatings for Softwoods," Symposium on Chem. Aspects of Wood Tech., Swedish Forest Prod. Res. Lab., Södergam, Stockholm, Sweden, 1981.

(4) Bravery, A.F. and Miller, E.R., "The Role of Pre-treatment in the Finishing of Exterior Softwood," Proc. of the Ann. Conv. of the British Wood Pres. Assoc., 1980, p. 14-23.

(5) Boxall, J., "Painting Weathered Timber," Information Sheet 20/77. Building Research Establishment, Princes Risborough Laboratory, Alyesbury, Bucks, England, 1977.

(6) Shurr, G.G., "Proper Coatings for Wood Exteriors," *Am. Painting Contractor*, *12*, 18 (1969).

(7) Desai, R.L., "Coating Adhesion to Weathered Wood," Eastern Forest Products Laboratory, Ottawa, Canada, *Bi-monthly Research Notes*, *23* (5), 36-37 (1967).

(8) Kleive, K., "Weathered Wooden Surfaces—Their Influence on the Durability of Coating Systems," JOURNAL OF COATINGS TECHNOLOGY, *58*, No. 740, 39 (1986).

(9) "Test Method D 905-49 (Reapproved 1981) for Strength Properties of Adhesive Bonds in Shear by Compression Loading," Annual Book of ASTM Standards, Vol 15.06, Philadelphia, PA, 1981.

(10) Strickler, M.D., "Specimen Designs for Accelerated Tests," *Forest Prod. J.*, *18* (9), 84 (1968).

(11) Hon, D.N.-S. and Ifju, G., "Measuring Penetration of Light into Wood by Detection of Photo-induced Free Radicals," *Wood Sci.*, *11* (2), 118 (1978).

(12) Duncan, D.B., "Multiple Range and Multiple F Tests," *Biometrics*, *11*, 1 (1955).

(13) Miniutti, V.P., "Properties of Softwoods that Affect the Performance of Exterior Paints," *Official* DIGEST, *35*, No. 460, 451 (1965).

(14) Miniutti, V.P., "Microscale Changes in Cell Structure at Softwood Surfaces During Weathering," *Forest Prod. J.*, *14* (12), 571 (1974).

(15) Feist, W.C. and Mraz, E.A., "Comparison of Outdoor and Accelerated Weathering of Unprotected Softwoods," *Forest Prod. J.*, *28* (3), 38 (1978).

(16) Black, J.M. and Mraz, E.A. "Inorganic Surface Treatments for Weather-resistant Natural Finishes," Research Paper FPL 232, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 1974.

(17) Smith, W.B., Côté, W.A., Vasishth, R.C., and Siau, J.F., "Interactions Between Water-Borne Polymer Systems and the Wood Cell Wall," JOURNAL OF COATINGS TECHNOLOGY, *57*, No. 729, 27 (1985).

(18) Tarkow, H., Feist, W.C., and Southerland, C.F., "Interaction of Wood with Polymeric Materials, Penetration Versus Molecular Size," *Forest Prod. J.*, *16* (10), 61-65 (1966).