Correlation Of Adhesive Strength With Service Life Of Paint Applied To Weathered Wood

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Summary: Smooth-planed western redcedar bevel siding was exposed outdoors (preweathered) for 1, 2, 4, 8, and 16 weeks. The weathered boards were separated into two end-matched groups. One group was painted with only primer paint and tested for paint adhesion following preweathering. The second group was painted with a primer and topcoat, exposed outdoors for an additional 17 years, and evaluated during this period for paint cracking and flaking. There was a direct correlation between the amount of time the siding was preweathered and the long-term paint performance. Those boards preweathered for 16 weeks began to show cracking after about 3 years, whereas those boards that were not preweathered were in almost perfect condition after 17 years. Paint adhesion tests done on end-matched boards that were preweathered at the same time and then painted showed good correlation between the paint bond strength and outdoor paint performance for the preweathered boards.

Keywords: Alkyd-based paint, latex-based paint, weathering, western redcedar, paint adhesion.

1 INTRODUCTION

In the absence of adhesion failure, paint on wood exposed outdoors gradually erodes. Degradation of paint by erosion may take a decade or more, depending on the degree of exposure to sunlight and moisture and the thickness and type of paint. While a paint system is eroding, it still protects the wood surface from degradation. Until this erosion process proceeds to the point where the primer begins to show, the paint surface can be renewed readily with an additional topcoat. With timely refinishing, painted wood can last for centuries (Feist & Hon 1984).

If, however, the paint–wood interphase 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 interphase failure is a degraded wood surface caused by weathering prior to initial priming with paint (Arnold *et al.* 1992, Boxall 1977, Bravery & Miller 1980, Desai 1967, Evans *et al.* 1996, Kleive 1986, Miller 1981, Shurr 1969, Thay & Evans 1998, Underhaug *et al.* 1983, Williams & Feist 1994, Williams *et al.* 1990). These previous studies have also shown that weathering of wood prior to painting (preweathering) decreases subsequent paint performance. However, the amount of preweathering has not been quantitatively linked to long-term paint performance. For example, no study has looked at how short periods of preweathering (one week, several weeks, a few months, several months) affect long-term paint performance (more than 10 years).

This study reports the results of paint adhesion tests on newly painted preweathered boards and paint performance after 17 years of outdoor exposure on boards that were similar to those used for the paint adhesion tests and that were also preweathered for the same amounts of time. The results clearly show the effect of short periods of preweathering (1 to 16 weeks) on the performance of three different paint systems (two different primers) exposed outdoors for 17 years. Paint performance is then compared with the adhesive tests previously performed on end-matched boards that were preweathered the same amount, then painted using the same two primers, but were not exposed outdoors after painting. The paint adhesion test results and paint performance after 14 years were reported in more detail earlier (Williams *et al.* 1987, Williams & Feist 2001).

2 EXPERIMENTAL

2.1 Materials

The finishes were applied to smooth-planed western redcedar (WRC) (*Thuja plicata* Donn) vertical-grained heartwood. The boards for the paint adhesion tests were finished with either two coats of alkyd-oil primer or two coats of latex primer, and the boards for the outdoor exposure were finished with either (1) solventborne water-repellent preservative (WRP), one coat of alkyd-oil primer, and one coat of acrylic latex topcoat (WRP/alkyd/latex); (2) one coat of alkyd-oil primer and one coat of acrylic latex topcoat (alkyd/latex); or (3) one coat of latex primer and one coat of acrylic latex topcoat (latex/latex).

finishes were commercial formulations. For each of the preweathering periods (0, 1, 2, 4, 8, and 16 weeks), 12 boards were exposed outdoors for 17 years.

2.2 Methods

Freshly planed vertical-grained WRC boards 410 by 100 by 10 mm (16 by 4 by 3/8 in.) (longitudinal by radial by tangential) were exposed outdoors, oriented vertically facing south 15 km west of Madison, Wisconsin, in the summer of 1984 for 1, 2, 4, 8, or 16 weeks. At the same time, controls (0-week specimens) were kept from exposure to sunlight in a darkened room at 27? C and 65% relative humidity for 16 weeks. Following weathering, the WRC boards were lightly washed with distilled water, air-dried, and painted. The boards were randomly divided into two groups. One group was finished with two coats of primer and was used to conduct paint adhesion studies. One half of each board used for paint adhesion tests was painted with alkyd-oil primer and the other half with acrylic latex primer. The second group was finished with the paint systems described in the previous section and placed back on the test fence in September 1984. Boards from all preweathering periods (1, 2, 4, 8, and 16 weeks) were used for the WRP/alkyd/latex paint system. Only boards preweathered for 0-, 1-, and 16-weeks were finished with the other two paint systems (alkyd/latex and latex/latex).

Boards for the adhesion tests were cured for 3 months, then freshly planed hard maple (*Acer saccharum*) boards were glued to the painted surfaces using an emulsion polymer/isocyanate (EPI) adhesive. The resulting panels were cured in a press at 520 kPa (75 lb/in^2) at room temperature for 36 hours. Tensile specimens and block shear specimens were cut from each assembled WRC/maple panel after the adhesive cured. Both had 25- by 25-mm (1- by 1-in.) bond areas. The tensile specimens were then glued to aluminum blocks **(**Fig. 1) using an epoxy/polyamide adhesive and were cured for 48 hours at room temperature.

Expanded cross sections of both the tensile and the shear specimens (Fig. 1) show several interphases: wood/paint, paint/EPI, and EPI/maple. In addition, the final tensile specimens had wood/epoxy and epoxy/aluminum interphases. Hard maple, being a stronger wood, shifted the failure toward the weaker WRC/paint interphase or to the WRC. The shear specimen was a further-modified version of the specimens as described in American Society for Testing and Materials (ASTM) D905 (ASTM 1981) and modified by Strickler (1968).

Tensile and shear specimens were subsequently equilibrated to 12% equilibrium moisture content (EMC) and tested at a constant-displacement load rate of 1 mm/min and 0.38 mm/min, respectively. 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 interphases was deemed unacceptable because only failures of the weathered wood substrate or of the WRC/paint interphase were considered pertinent. Accordingly, all specimens were visually examined for failure following testing, and only those exhibiting the specified failure type were used to compare adhesion.

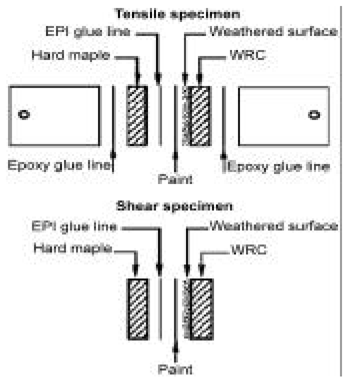

Figure 1. Expanded view of tensile and shear specimens showing interphases (ML86-5258)

For outdoor exposure, three boards were mounted together to form a panel configured as lap siding. Four panels were tested for each preweathering time. The boards were evaluated annually according to ASTM standards for erosion (ASTM 1991a), cracking (ASTM 1991b), and flaking (ASTM 1991c). Each board in the panel was rated individually, resulting in 12 observations for each category (flaking and cracking), annually or biannually for 17 years. A rating of 10 indicates no observable degradation, and 1 indicates complete failure of the specimen. A rating of 5 indicates sufficient degradation to warrant normal refinishing if the finish was in use on a structure.

3 RESULTS AND DISCUSSION

3.1 Adhesion tests: latex primer

3.1.1 Tensile tests

Many specimens weathered less than 4 weeks before painting failed within the WRC substrate, and this was attributed to cohesive failure in the wood and not to weathering. This wood failure occurred away from the interphase 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 (Hon & Ifju 1978). Specimens weathered for 8 or 16 weeks failed almost exclusively at the paint/wood interphase.

A plot of all failures in the tensile tests of latex primer is shown in Fig. 2. A Duncan multiple range test of means (Duncan 1955) showed no difference between controls and specimens exposed for 1, 2, and 4 weeks. The distribution in tensile strengths from 0 to 4 weeks (Fig. 2) is probably attributable to wood variation not paint adhesion. Mean tensile strength remains constant for up to 4 weeks, then as interphase 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 (Fig. 3). The mean tensile strength of the wood/latex primer bond decreased from 2.1 MPa (310 lb/in^2) after weathering for 4 weeks to 1.0 MPa (150 lb/in^2) after weathering for 16 weeks (Table 1).

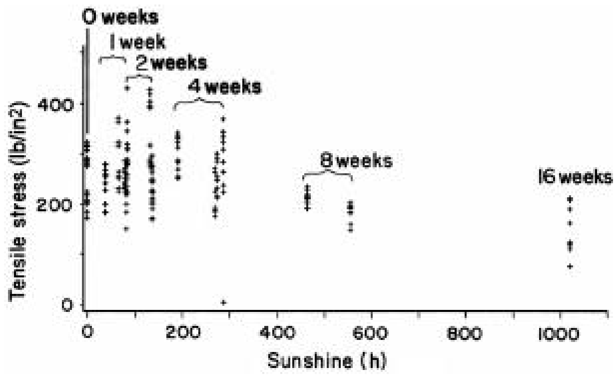

Figure 2. Ultimate tensile stress compared with sunlight exposure time of acrylic latex primer on WRC. All adhersive failures and cohesive wood failures are shown (1 lb/in^2 = 6.9 kPa) (ML86 5259).

The mean tensile and shear strength at failure for both paints are listed in Table 1. Using a linear model, a Duncan's multiple range test of means shows significant (alpha = 0.05) loss of adhesion for all groups after 4 weeks of weathering. A 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 did the oil primer. This probably relates more to physical differences between the two paints than to weathering effects.

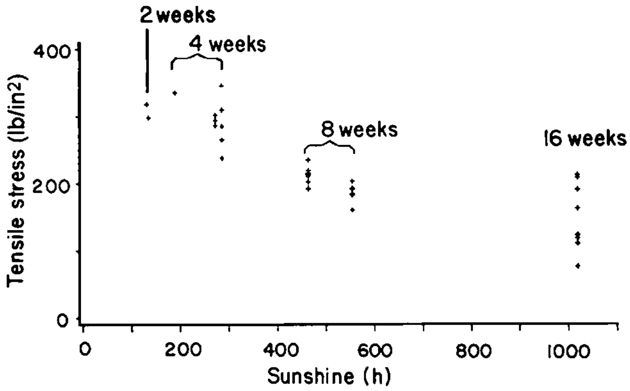

Figure 3. Ultimate tensile stress compared with sunlight exposure time of acrylic latex primer on WRC. Only primer/wood interphase failures are shown (1 lb/in^2 = 6.9 kPa) (ML86 5260).

Table 1—Results of a Duncan multiple range test on mean adhesive strength of wood/primer at Alpha = 0.05[a]

	Tensile test						Shear test					
	Amount of preweathering						Amount of preweathering					
	0	1 week	2 weeks	4 weeks	8 weeks	16 weeks	0	1 week	2 weeks	4 weeks	8 weeks	16 weeks
Latex primer[b]												
Number flaking[c]	0	0	2	10	15	10	24	11	24	24	12	6
Strength (lb/in^2)	—	—	310	305	200	150	800	765	750	710	560	450
Strength (MPa)	—	—	2.1	2.1	1.4	1.0	5.5	5.3	5.2	4.9	3.9	3.1
Alkyd-oil primer[d]												
Number flaking[c]	0	0	19	14	18	6	7	0	15	22	12	6
Strength (lb/in^2)	—	—	190	255	155	125	690	—	700	675	530	490
Strength (MPa)	—	—	1.3	1.8	1.1	0.87	4.8	—	4.8	4.7	3.7	3.4

[a]Strength values underlined by the same line are not significantly different, with 95% confidence.
[b]For latex primer, R^2 = 0.782 in tensile test and R^2 = 0.591 in shear test.
[c]Number of specimens flaking at the paint/wood interphase.
[d]For alkyd-oil primer, R^2 = 0.579 in tensile test and R^2 = 0.455 in shear test.

3.1.2 Shear tests

In the shear test, there was little wood substrate failure because failures occurred primarily at the latex primer/wood interphase with essentially 100% primer adhesion failure on the 8- and 16-week specimens (Fig. 4). The shear results were similar to the tensile results and showed no significant differences in mean shear strengths of 5.5, 5.3, and 5.2 MPa (800, 765, and 750 lb/in^2), respectively, for specimens exposed for 0, 1, or 2 weeks. The 4-week specimens were statistically different than the controls but not different than the 1- and 2-week specimens (Table 1). The decrease in adhesion after 4 weeks of exposure is evident in Fig. 5. The decrease in strength for the controls from 5.5 MPa (800 lb/in^2) to 3.1 MPa (450 lb/in^2) after 16 weeks was not as great as with the tensile values (Table l). However, the trend was the same. As with the tensile tests, failure at the primer/EPI and the EPI/maple interphases was ignored and only the results from specimens that failed at the wood/primer interphase were plotted.

3.2 Adhesion tests: alkyd-oil primer

3.2.1 Tensile tests

The mean tensile strength of the oil primer on wood weathered 4 weeks before painting was 1.8 MPa (255 lb/in^2) compared with 870 kPa (125 lb/in^2) after 16 weeks of weathering (Table 1). As with the latex primer, ultimate strength for many specimens weathered 2 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) (Fig. 4). This failure of the earlywood/paint interphase rather than the latewood/paint interphase is opposite to the expected failure site.

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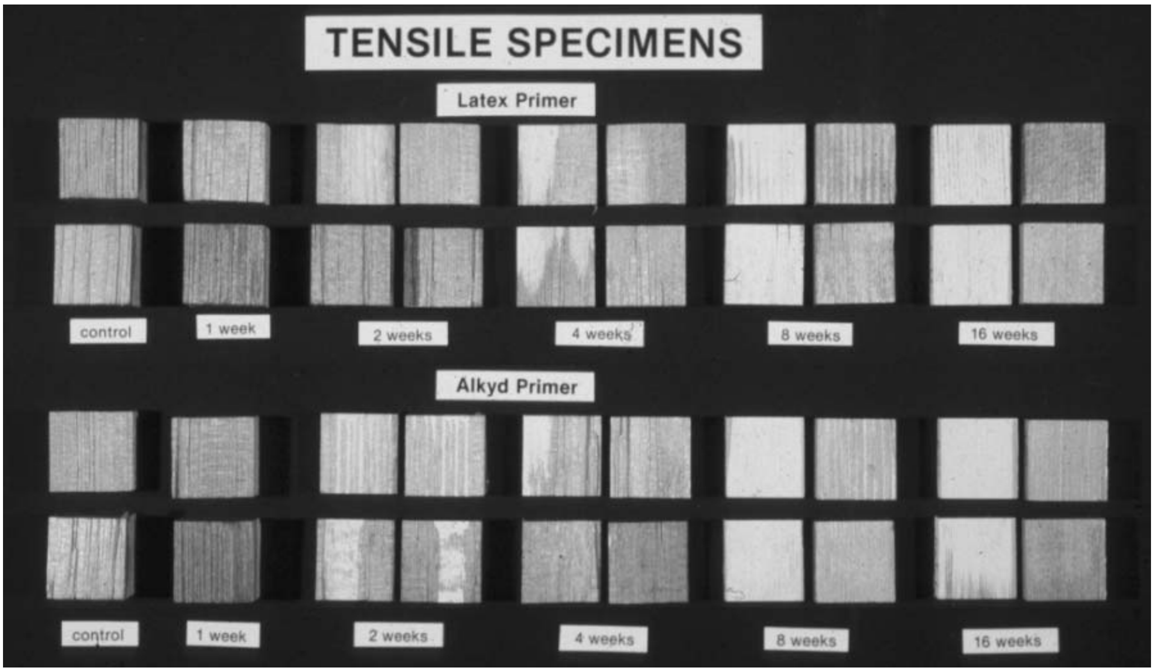

Figure 4. Failure surfaces of representative tensile specimens (M86 0043).

With both paints, the differences in the elastic modulus of earlywood and latewood bands in wood may set up stress concentrations at the junction of these bands. The flexible latex primer film may more easily absorb this differential strain energy without failing. The less flexible oil primer cracks at the strain energy levels along the earlywood/latewood boundaries, failing at lower loads than the latex primer. This type of crack formation of oil primer at the earlywood/latewood boundary has previously been reported (Miniutti 1965, 1974). 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 than for latex primer. This may be caused by the higher adhesive strength to the latewood. However, as mentioned, the greater adhesion of the oil primer to latewood was unusual because it is fairly well accepted that paint adheres better to earlywood. Apparently, this traditional view of better paint adhesion to earlywood is appropriate only for unweathered wood.

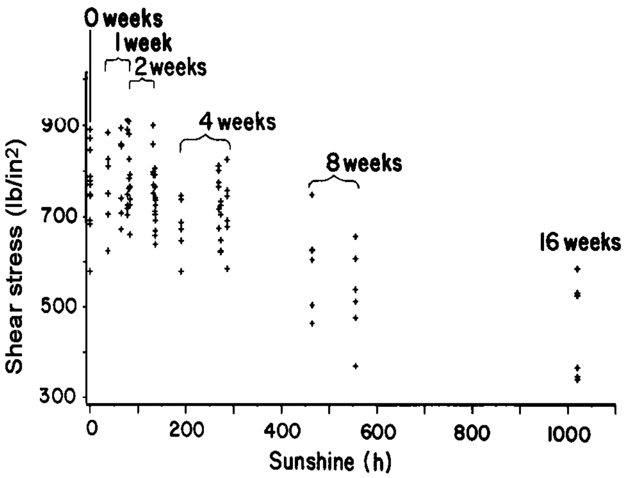

Figure 5. Ultimate shear stress compared with sunlight exposure time of acrylic latex primer on WRC. Only primer/wood interphase failures are shown (1 lb/in^2 = 6.9 kPa) (ML86 5261).

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The results of these experiments showed no difference between earlywood and latewood adhesion for the controls and the 1-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. Although only a few of the 2-week-weathered specimens failed at the earlywood/paint interphase, this apparent anomaly became the general failure site in the specimens weathered 4, 8, and 16 weeks before painting (Fig. 4). The differential failure of the oil primer on earlywood/latewood boundary and the uniform failure of the latex paint may be explained by the difference in the interphase formed by these different paints with the weathered wood surface.

3.2.2 Shear tests

The change in shear strength of oil primer with time shows the same trend as the tensile results. The mean adhesion strength dropped from 4.8 to 3.4 MPa (700 to 490 lb/in^2) between no preweathering and 16 weeks of preweathering (Table 1). As observed in the tensile tests, the shear specimens showed that the oil primer adhered stronger to weathered latewood than did the latex primer.

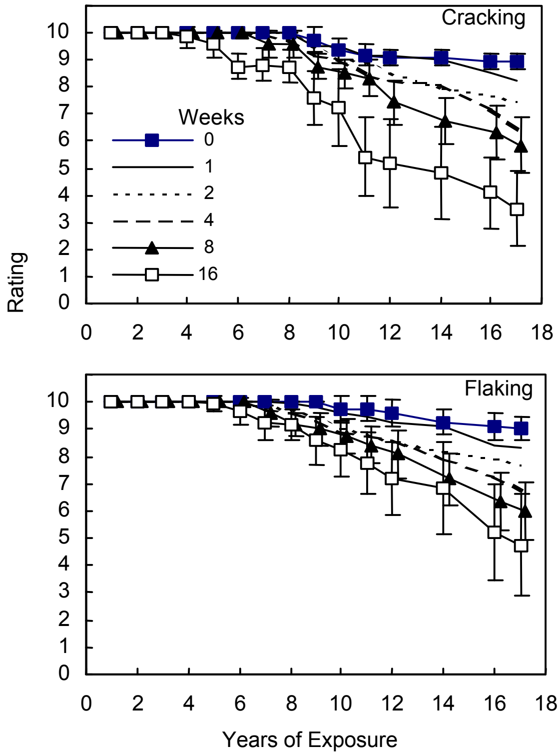

Figure 6. Paint evaluations for cracking and flaking during 17 years for the paint system of solventborne water-repellent preservative, one coat of alkyd-oil primer, and one coat of acrylic latex topcoat (WRP/alkyd/latex). The data points are the average of 12 observations, and the bars give the standard deviation.

3.3 Outdoor weathering of paint: cracking and flaking

The most notable differences among the finishes were found for cracking and flaking. The effect of preweathering on these paint degradation mechanisms were evaluated for 17 years for the three different paint

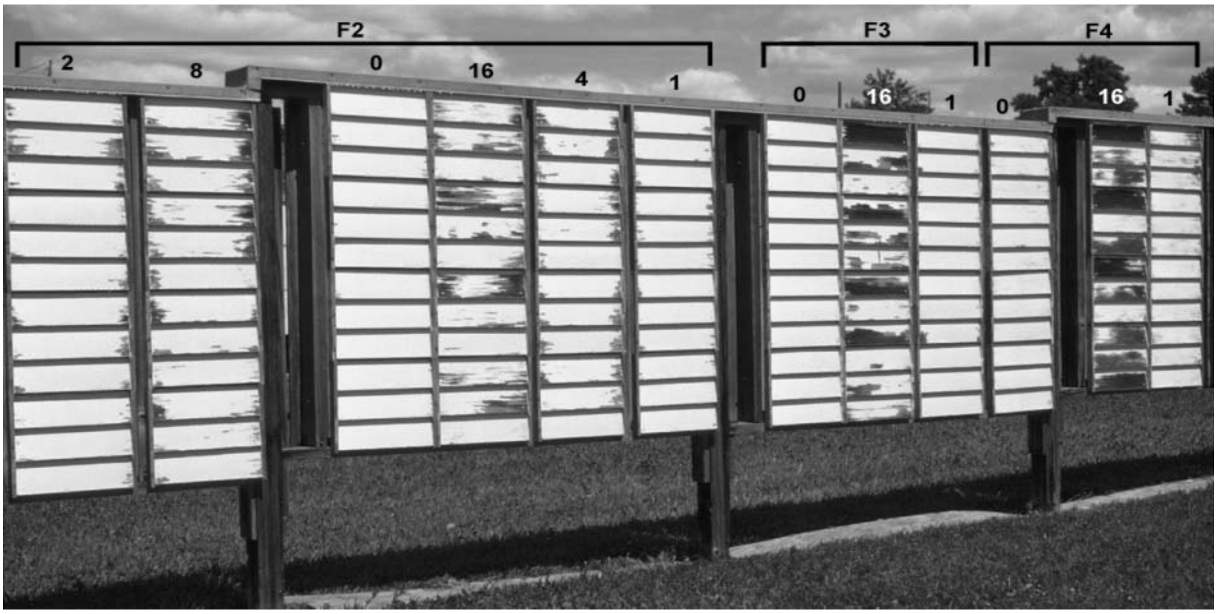

Figure 7. Exposure fence west of Madison, Wis., showing painted specimens after 17 years of outdoor exposure (F2, WRP/alkyd/latex; F3, alkyd/latex; F4, latex/latex; numbers are weeks of preweathering).

systems. In addition to the effect of preweathering on paint degradation, the experimental design also included the effects of a WRP pretreatment and an oil-alkyd versus a latex primer. Depending on the amount of preweathering, the boards painted with any of the three paint systems began to show cracking during the exposure period. Flaking generally followed cracking after a year or two (Fig. 6). Differences in paint performance after 17 years of exposure for the different preweathering periods can clearly be seen in Figure 7. Each vertical section contains 12 replicates for the different preweathering periods. For the three paint systems, boards that were not preweathered are in excellent condition, whereas boards that were preweathered for 16 weeks have failed. There is considerable variation among the 12 replicates of the 16-week preweathered boards, but the trends are obvious.

3.3.1 WRP/alkyd/latex paint system

The effect of preweathering can clearly be seen in the cracking and flaking evaluations during the 17 years. The boards with 16 weeks of preweathering began to show signs of cracking after only 3 years of exposure, whereas those with 0 and 1 week of preweathering began to crack after 9 years. Clearly, each preweathering period had different performance results. This difference in performance can be seen in the photographs of the boards after 17 years of exposure (Fig. 8a–f). One panel (3 of the 12 boards) for each of the preweathering times is shown. The other three panels showed the same trend. Although it is not apparent in cracking results in Figure 6, there is clearly a slight difference in performance between the 0- and 1-week preweatherings (Fig. 8a and b). The control (0-week preweathering) was in almost perfect condition after 17 years of exposure. That is a service life of more than 17 years for a paint system comprised of a WRP pretreatment, one coat of primer, and one topcoat. The slight discoloration just under the bottom edge of each board is dirt.

3.3.2 Alkyd/latex paint system

The cracking and flaking ratings for the 16-week preweathering periods are slightly lower for the alkyd/latex paint system without the WRP (Fig. 9) than for the specimens with the same amount of preweathering finished with the WRP/alkyd/latex paint system (Fig. 8). This can be seen by comparing photographs of panels from the different paint systems preweathered for the same amount (Fig. 10a, b, and c compared with Fig. 8a, b, and f). After 17 years, there was a slight improvement in paint performance in boards pretreated with a WRP compared with those without the pretreatment, particularly for boards that had been preweathered. There was no apparent difference for the control boards. Paint cracking developed more quickly on boards without WRP. Also there appears to be a slight difference between the 0- and 1-week preweathering periods for boards without the WRP pretreatment (Fig. 9). For WRP-treated boards, flaking occurred about 1 to 3 years after cracking. However, for boards without WRP, flaking was immediately evident upon cracking.

3.3.3 Latex/latex paint system

In general, ratings for the performance of the alkyd/latex paint system (Fig. 9) were slightly higher than those of the latex/latex paint system (Fig. 11). There was clearly a difference between the two paint systems within the 0-, 1-, and 16-week preweathering periods. Both the alkyd/latex (Fig. 9) and the latex/latex (Figs. 11 and 12) paint systems started cracking and flaking about the same time (after 3 to 4 years of exposure), but the latex/latex system degraded faster in subsequent years. For the latex/latex paint system, the paint on the 0-week preweathered boards cracked and flaked sooner than expected given the inherently greater flexibility of the latex/latex paint system compared with the alkyd/latex system.

3.4 Paint adhesive strength compared with cracking and flaking evaluations

Figure 13 shows the average adhesive strength of the alkyd-oil primer compared with the cracking or flaking evaluations for the WRP/alkyd/latex paint system for specimens preweathered for 2 to 16 weeks. There appears to be a good correlation even though there was considerable cohesive wood failure in the specimens preweathered for only 0, 1, and 2 weeks. The tensile strength of WRC perpendicular to grain is about 1.5 MPa and the shear strength parallel to grain is about 6.8 MPa (Forest Products Laboratory 1999, table 4-3a). Therefore, the regression analysis included only data pertaining to paint/wood bond strength. Even those specimens preweathered for 2 weeks had sufficient paint adhesive strength to cause primarily wood failure in the adhesion tests. This was less of a problem with the shear tests because the shear strength of WRC parallel to grain was somewhat higher than the paint/wood shear strength for the 2-week preweathered specimens.

If any part of the paint bond was visible after the adhesion test, the specimen was included in the data set. In Fig. 13c and d (tensile strength versus cracking and flaking), the abrupt drop for the 2-week preweathered specimens is probably caused by a failure in the wood. The R^2 values for the comparisons of shear strength with cracking or flaking were 0.81 and 0.98, respectively. The R^2 values for the comparisons of tensile strength with cracking or flaking were 0.61 and 0.56, respectively. If the 2-week preweathering data are removed from the data set, the R^2 values are 0.73 and 0.97 for cracking and flaking, respectively Thus, it appears that paint adhesion tests give a reasonable indication of long-term performance of paint. Paint performance without cracking and flaking seems to require a shear strength of at least 5.0 MPa and a tensile strength of 1.8 MPa on smooth-planed WRC.

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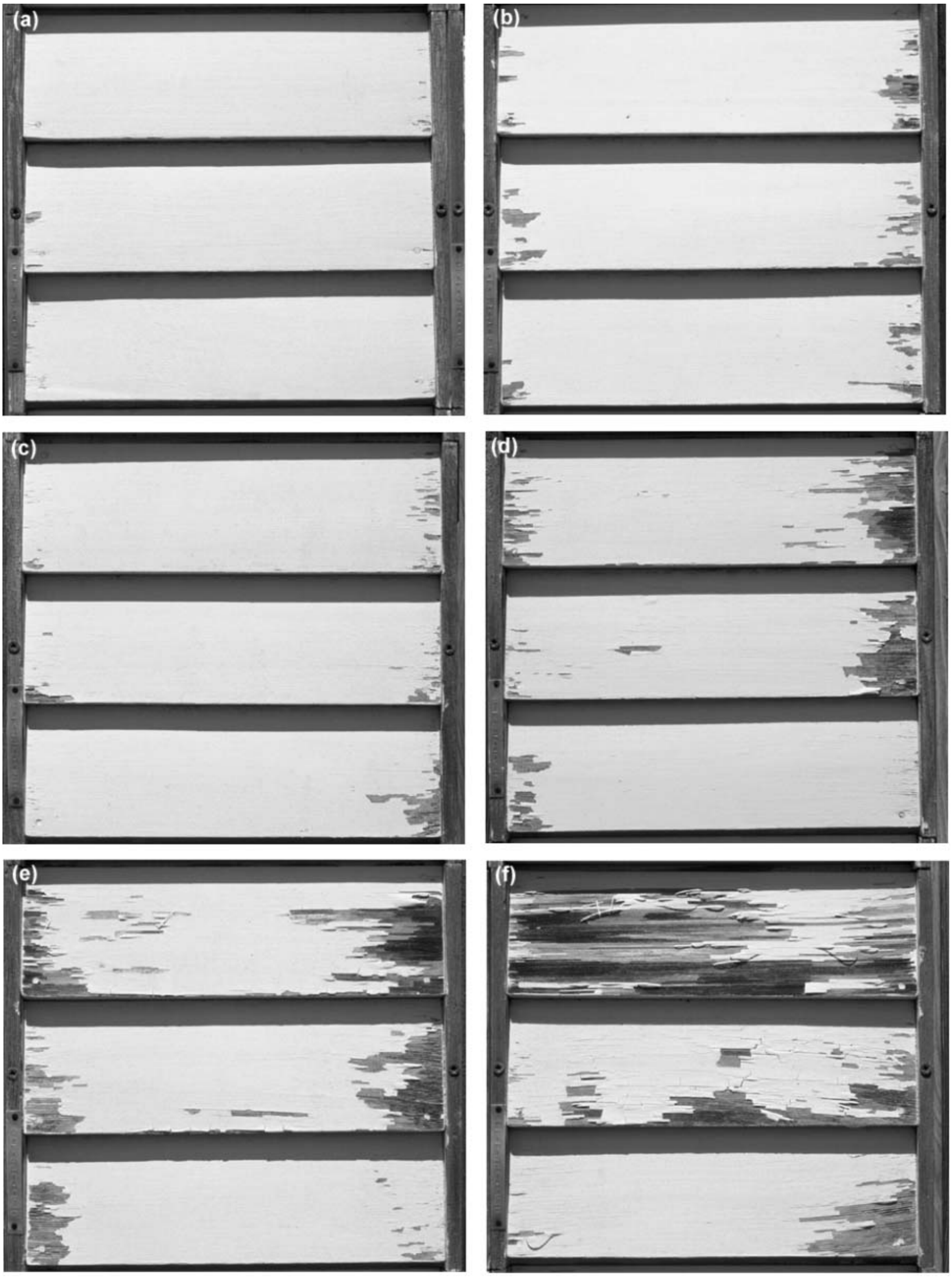

Figure 8. Examples of panels painted with a solventborne water-repellent preservative, one coat ofalkyd-oil primer, and one coat of acrylic latex topcoat (WRP/alkyd/latex) after 17 years of outdoorexposure. (a) control, no exposure prior to painting, (b) preweathered 1 week, (c) preweathered 2 weeks, (d) preweathered 4 weeks, (e) preweathered 8 weeks, and (f) preweathered 16 weeks.

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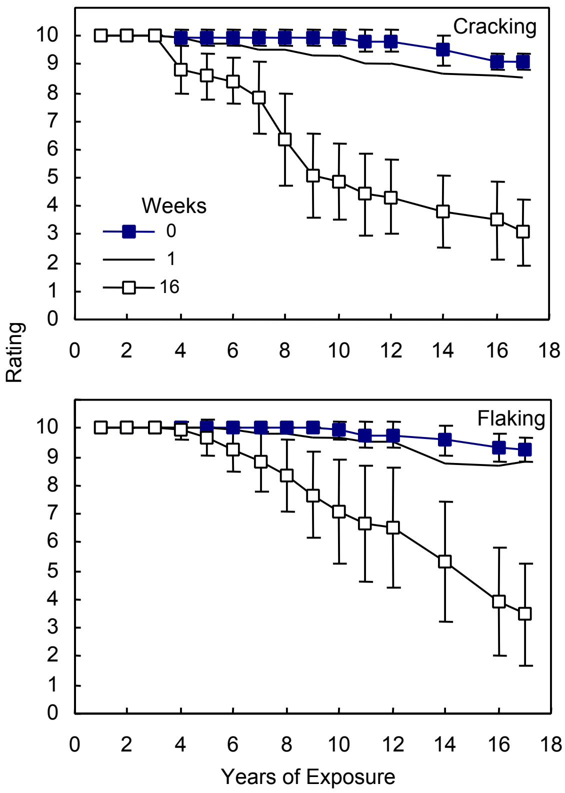

Figure 9. Paint evaluations for cracking and flaking during 17 years of outdoor exposure for specimens painted with one coat of alkyd-oil primer and one coat of acrylic latex topcoat (alkyd/latex). The data points are the average of 12 observations, and the bars give the standard deviation.

4 CONCLUSIONS

The exposure of unpainted smooth-planed, vertical-grained WRC siding to weather for as little as 1 to 2 weeks can shorten the service life of subsequently applied paints. For wood exposed unfinished for 16 weeks prior to painting, cracking in the paint film was detected after only 3 years of outdoor exposure. In contrast, boards that were not exposed to the weather prior to painting were in almost perfect condition after 17 years of exposure. Paint adhesion tests gave a good indication of service life for those specimens exposed 4 or more weeks prior to painting.

However, the adhesion tests did not indicate potential problems with cracking and flaking for specimens preweathered for short periods because the paint/wood bond strength was about the same as the wood strength. The outdoor performance of painted wood that had been preweathered for short periods showed that there was undoubtedly some surface degradation of these specimens caused by the preweathering. It is imperative that smooth-planed lumber be painted promptly during construction.

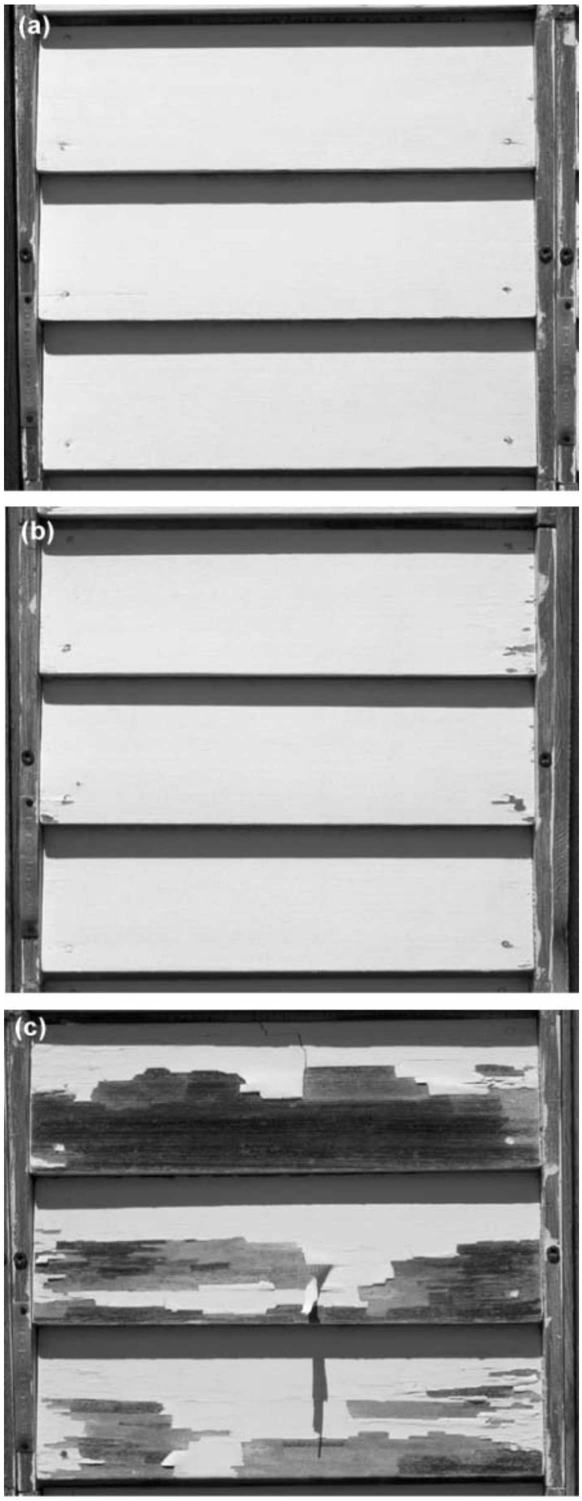

Figure 10. Examples of panels painted with one coat of alkyd-oil primer and one coat of acrylic latex topcoat (alkyd/latex) after 17 years of outdoor exposure. (a) control, no exposure prior to painting, (b) preweathered 1 week, and (c) preweathered 16 weeks.

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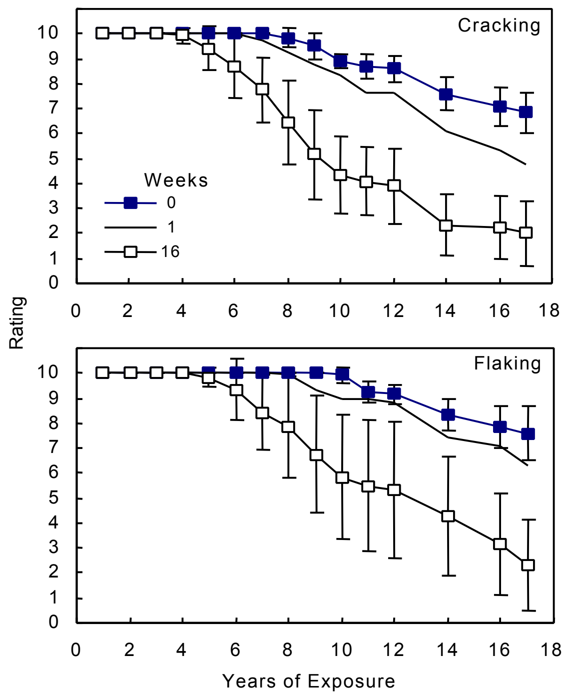

Figure 11. Paint evaluations for cracking and flaking during 17 years of outdoor exposure for specimens finished with one coat of latex primer and one coat of acrylic latex topcoat (latex/latex). The data points are the average of 12 observations, and the bars give the standard deviation.

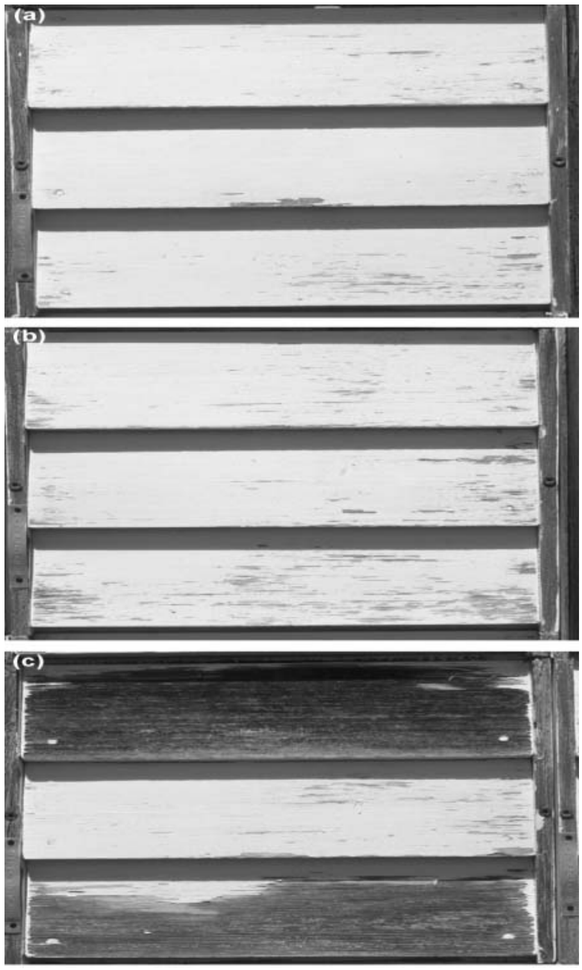

Figure 12. Example of panels painted with one coat of latex primer and one coat of acrylic latex topcoat (latex/latex) after 17 years of outdoor exposure. (a) control, no exposure prior to painting, (b)preweathered 1 week, and (c) preweathered 16 weeks.

5 ACKNOWLEDGMENTS

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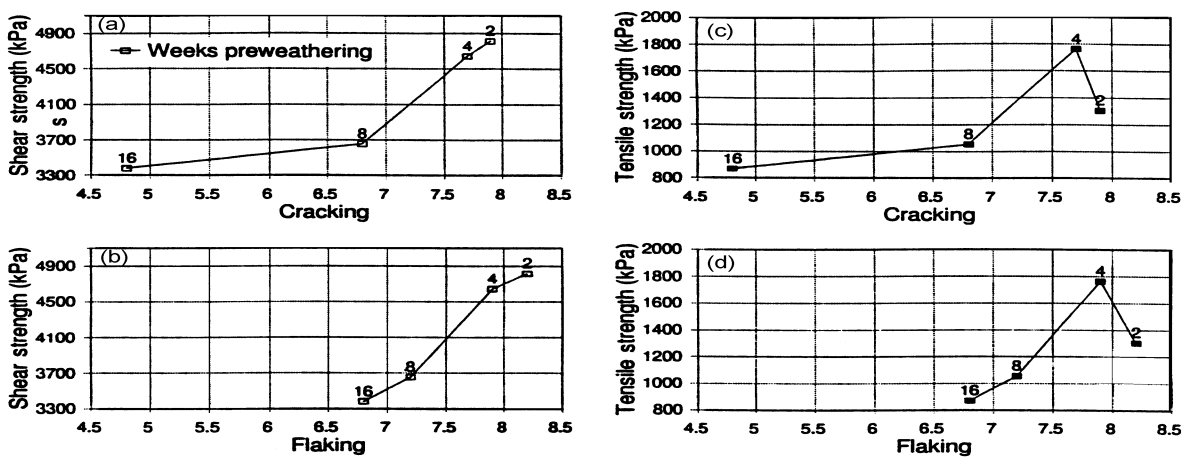

Figure 13. Paint adhesive strength (shear and tension) of the alkyd-oil primer compared with the cracking or flaking evaluations of the WRP/alkyd/latex paint system after 17 years of outdoor exposure. (a) shear strength versus cracking, (b) shear strength versus flaking, (c) tensile strength versus cracking, and (d) tensile strength versus flaking. The number of weeks of preweathering is shown with each data point. The R2 values are 0.81, 0.98, 0.61, and 0.56 for (a) through (d), respectively. If the 2-week data are not included in the regression analysis for (c) and (d), the R2 values are 0.73 and 0.97, respectively.

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