Comparison of Traditional Methods for Testing Paint Service Life With New Methods for Service Life Prediction

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ABSTRACT

Western redcedar siding was "preweathered" by placing it outdoors for 1, 2, 4, 8, or 16 weeks prior to being painted. Panels were painted following the preweathering and tested for paint adhesion. The amount of time these panels were exposed (preweathered) directly affected paint adhesion. As much as 50% paint adhesion loss was shown for specimens preweathered for 16 weeks. For matching panels that were painted and exposed outdoors, the longer the panels were preweathered, the shorter the service life of the paint: The paint on panels preweathered for 16 weeks began to flake and peel after 4 to 5 years; for 8 weeks, after 7 to 8 years; for 4 weeks, after 9 to 10 years; for 2 weeks, after 10 to 11 years; and for 1 week, after 13 years. Unexposed controls were still in almost perfect condition after 17 years of exposure, This work spanned 17 years — there must be a more timely means of getting this kind of information.

In recent outdoor exposure studies, the response of materials was measured directly every few minutes during exposure and this response was matched to the weather causing the response. Changes in specimens could be observed as they occurred. This work involved measuring the load and deflection of sealants, but the methods that were developed may be useful for many materials. By measuring materials response and weather during outdoor exposure, early failures could be linked directly to their causes.

INTRODUCTION

In 1987, we reported the effect of short periods of weathering of unpainted wood on the adhesion of subsequently applied paint. (Williams et al. 1987) A second objective of this previous work was to determine if the adhesion tests could predict the performance of matched painted boards placed outdoors at our test site near Madison Wisconsin. The paint on the matched boards had decreased service life commensurate with the amount of weathering prior to painting (preweathering) and decreased paint adhesion (Williams and Feist 2001). There was a reasonable correlation between loss of adhesive strength and cracking/flaking evaluations over 17 years of outdoor exposure (Williams et al. 2002). As these studies progressed, it became apparent that we needed more timely evaluation of our specimens during the outdoor exposure and better correlation of the evaluations with the weather conditions. We have accomplished this in recent field studies of sealants (caulking compounds).

To develop service-life prediction methods for the study of sealants, a fully instrumented weather station was installed at the Forest Products Laboratory (FPL) outdoor test site near Madison, Wisconsin, USA (latitude 43° N). Temperature, relative humidity (RH), rainfall, ultraviolet (UV) radiation at 18 wavelengths, and wind speed and direction are being continuously measured and recorded. The weather data were integrated over time to calculate the dose of the weathering factors. Sealant test specimens were installed in a specially designed apparatus that subjected them to weather-induced cyclic movement that forced a load and deflection on the specimens. Load-deflection information and weather were correlated to yield information on critical factors affecting sealant performance. The results showed a clear link between sealant response during weathering and weather conditions causing this response. Instrumentation of the outdoor test facility and the data collection system are briefly described and methods for analyzing data are evaluated.

The overall objective of these studies was to develop protocols for predicting the service life of materials. Comparisons of paint adhesion tests on newly painted boards and paint performance after 17 years of outdoor exposure clearly show the effect of short periods of preweathering (1 to 16 weeks) on the performance of three different paint systems. Ultimately our goal is to use the information from outdoor materials response and weather data to develop appropriate accelerated tests and the capability to determine service life in less than real time with statistical confidence and reasonable accuracy. The traditionally accepted methods used to evaluate the service life of painted wood are compared with newly developed experimental methods now being used for testing sealants.

BACKGROUND

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. If, however, the paint–wood interphase fails, the paint film will debond within a short time and the paint will blister, crack, and peel. 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 also showed that weathering of wood prior to painting (preweathering) decreased subsequent paint performance. However, the amount of preweathering has not been quantitatively linked to long-term paint performance (more than 10 years).

General guidelines for accelerated testing of sealants are described by ASTM C 1442, Standard Practice for Conducting Tests on Sealants using Artificial Weathering Apparatus (ASTM 2000). Other ASTM methods for accelerated weathering of sealants are C 718-93 (UV-Cold Box Exposure of One-Part, Elastomeric, Solvent-Release Type Sealants), C 732–95(Aging Effects of Artificial Weathering on Latex Sealants), C 734–93 (Low-Temperature Flexibility of Latex Sealants After Artificial Weathering), C 793–97 (Effects of Accelerated Weathering on Elastomeric Joint Sealants), C 1257 (Accelerated Weathering of Solvent-Release-Type Sealants), and D 2249 (Predicting Effect of Weathering on Face Glazing and Bedding Compounds on Metal Sash) (ASTM 2000). These tests use a weathering device with UV radiation and intermittent water spray to accelerate degradation. The tests are not meant to predict the exact service life nor the mechanism of failures but are more of a qualitative evaluation of sealant perfomance. A sealant test that combines cyclic stress (fatigue), water immersion, and temperature change was initially developed by Hockman at NIST (ASTM C 719-93, Adhesion and Cohesion of Elastomeric Joint Sealants Under Cyclic Movement (ASTM 2000)-the so-called Hockman cycle). Specimens are rated visually for cohesive or adhesive failure. Studies on the correlation of long-term artificial aging and outdoor exposure of sealants that focused on the degradation of cohesive properties and surface appearance were reviewed by Wolf (1999).

Several devices have been previously used to induce cyclic movement (fatigue) of sealants during exposure. These devices have generally used thermally induced dimensional change to generate fatigue. For example, Onuoha (1999) used unplasticized polyvinyl chloride (PVC) pipe to produce fatigue in one-part polyurethane and polyurethane-hybrid sealants. Racks have also been built using dissimilar materials such as wood and aluminum (Brown 1965), concrete and aluminum (Burstrom 1980), and steel and aluminum (Karpati et al. 1977) to develop fatigue stresses. Manually operated devices have also been used to create cycling effects (Lacasse 1994).

EXPERIMENTAL

Paint adhesion tests

Materials

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 (alkydlatex), or (3) one coat of latex primer and one coat of acrylic latex topcoat (latex/latex). All 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.

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 5 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% RH 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 (alkydlatex 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 h. 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 (Figure 1) using an epoxy/polyamide adhesive and were cured for 48 h 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 (*Acer saccharum*), being a much denser, 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.

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.

Sealant weathering

Test Apparatus

The test apparatus subjects the specimens to movement in response to weather changes. The weather-induced movement of sealant specimens is obtained from the dimensional change in tangential blocks of red oak (*Quercus rubra*) as the wood wets and dries, from precipitation and/or changes in RH. Because the movement of the wood causes the cyclic movement, it is referred to as the "wood engine."

Two designs (TS and CS) were developed for conducting these exposure tests. In TS (Fig. 2), the test specimens are placed in tension (T) by an increase in moisture content of the wood (as the wood swells (S)). This subjects the specimen to stresses similar to that obtained via thermal expansion or contraction of metals, glass, ceramics, or polymers. This apparatus simulates the thermally driven designs previously used, but it is driven primarily by changes in RH and water, not temperature. In CS (Fig. 3), the test specimens are placed in compression (C) as the wood swells, which subjects the specimens to stresses similar to that obtained when sealants are used on wood.

The wood moves against an aluminum frame to produce a cyclic movement. The aluminum is attached to the bar at the top of the apparatus; the load cell and specimen are uni-axial and are connected using a stainless steel threaded rod with locking nuts (Fig. 4). All fasteners in the apparatus are stainless steel. Each specimen can be attached to a linear variable differential transformer (LVDT). However, we found that deflection could be determined using only four LVDTs. The LVDTs are sealed sensors with a

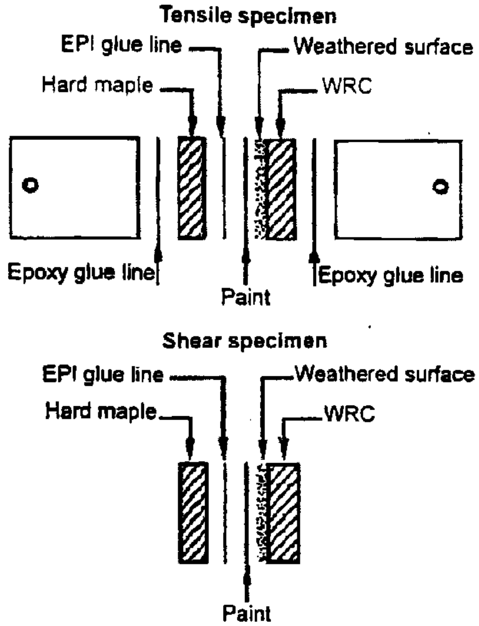

Figure 1. Expanded view of tensile and shear specimens showing interphases (ML86-5258)

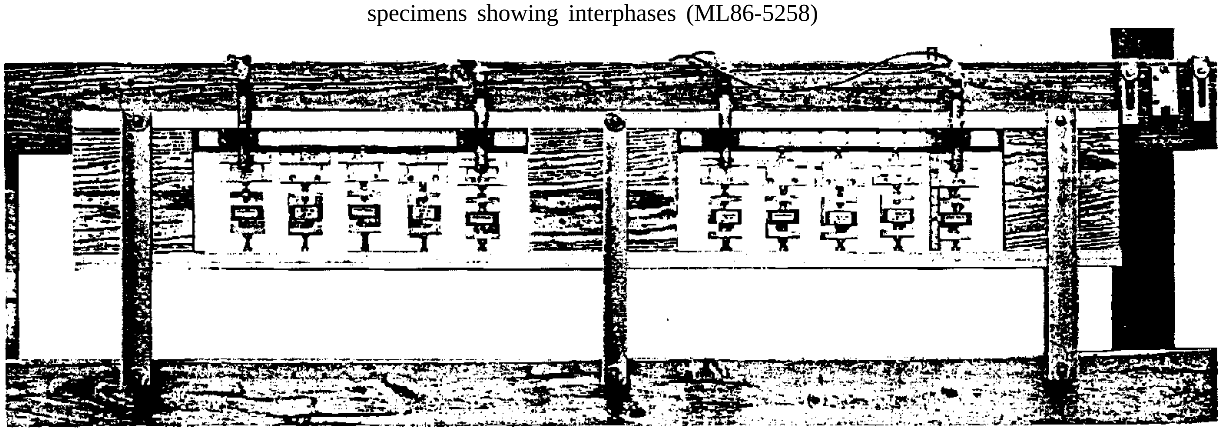

Figure 2. The CS-type outdoor exposure apparatus showing the wood engines (left, right, and center) and 10 specimens (5 on each side). Load cells are uniaxial with each specimen, and 4 of the specimens have LVDTs attached. As the wood swells, it increases the gage length of the sealant specimen.

deflection range of ±6.35 mm. Force transducers (load cells) are used to measure the load in the system. The sealed transducers have a capacity of ± 1111N.

Data Acquisition

Data from the force transducers and LVDTs were fed into a Keithley data acquisition system. The field site and main laboratory are linked by computer. Data were collected using a custom program written in LabView. This program periodically collects voltage measurements from the Keithley system, data from the UV radiation spectrometer (SR-18), and the weather instrumentation. The program then calculates force, deflection, stress, and strain based on the collected voltages. The result of the collection and calculation are called a "point." After 10 points have been collected, the program averages the values and appends the result to a tab-delimited data base.

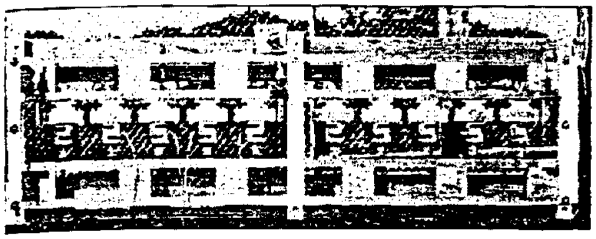

Figure 3. The TS-type outdoor exposure apparatus showing wood engines (6 wood blocks spaced across the top and 6 across the bottom). Load cells are uniaxial with each specimen, and 3 of the specimens have LVDTs attached. As the wood swells, it decreases the gage length of the sealant specimen.

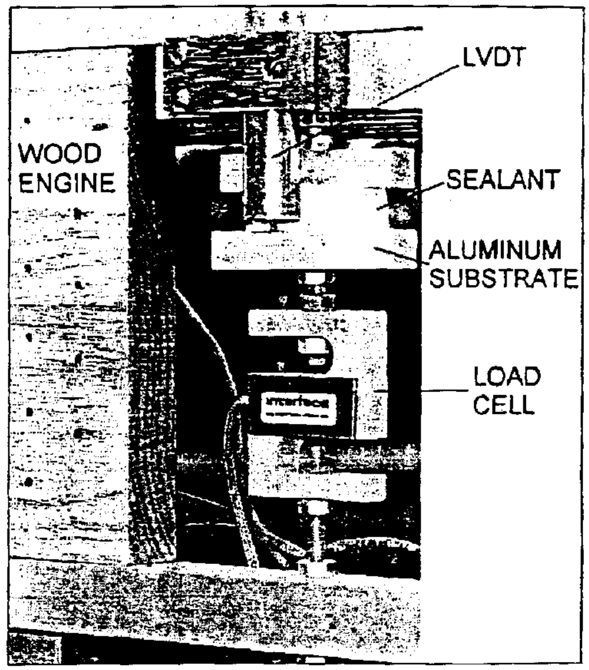

Figure 4. Detail view of specimen mount.

The data collection rate varies depending on the rate of movement of the specimens. During periods of rapid movement, more data are collected. As movement slows, the rate of data collection slows. During periods of rapid movement, a measurement is recorded every 2.5 min (average). At the other extreme, a measurement is recorded every 25 min (average).

UV Radiometer

UV measurements were made using a UV radiometer developed by the Smithsonian Environmental Research Center (SERC), Edgewater, Maryland. Personnel at SERC maintain the calibration of the instrument, and this calibration is traceable to NIST standards. The instrument, designated as SR-18, is one of a network of similar instruments located at various sites within the United States. UV radiation intensity is collected at the following wavelengths (in nanometers (nm)): 289.94, 291.30, 293.70, 295.93, 297.68, 299.70, 301.14, 303.75, 305.66, 307.47, 309.71, 312.22, 314.14, 315.76, 318.24, 319.96, 321.93, and 323.45. The radiometer is located on a tower 4 m above the ground; except for some trees located 200 m away, the view of the horizon is unobstructed in all directions.

Weather Station

The weather station has a modular design, which permits flexibility in terms of the type of sensors that can be used and the ability to modify the system to meet future needs. The weather station provides measurements of temperature, precipitation, barometric pressure, wind velocity, and RH. Data are stored locally in a tab-delimited database as hourly averages; however, 1-min data are extracted for calculations.

Materials

All wood engines were made from 25.4-mm- (1-inch-) thick flat sawn red oak (*Quercus rubra*). To enhance the rate of moisture content change, 3.2-mm- (1/8-inch-) diameter holes were drilled through the oak blocks. The end grain was sealed to minimize checking. The oak block engines were installed in the test apparatus with the grain perpendicular to the strain direction so that the direction of maximum dimensional change was parallel to the specimen strain direction. For both sealant test apparatuses, total wood width was 178 mm (7 inches) in the strain direction (Figs. 2 and 3).

Structural components of the apparatuses were made from aluminum because of its relatively high strength to weight ratio and corrosion resistance. The frames were made from 6061-T6 aluminum. Sealant specimen substrates were made from 6063-T52 anodized aluminum. Stainless steel hardware was used because of its resistance to corrosion. All fasteners (nuts, bolts, screws, and threaded rod) were 304 (18-8) stainless steel. The 4-40 threaded rod used to attach the LVDT cores to the apparatus was 303 stainless steel. The contribution of the thermally induced dimensional change of the aluminum and stainless steel components was minor compared with the moisture-induced dimensional change of the wood.

RESULTS AND DISCUSSION

Paint adhesion tests: latex primer

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. Specimens weathered for 8 or 16 weeks failed almost exclusively at the paint/wood interphase with no cohesive wood failure. A plot o all failures in the tensile tests of latex primer is shown in Figure 5. 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. 5) is probably attributable to wood variation, not paint adhesion. Mean tensile strength remains constant for up to 4 weeks, then as the paint–wood 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. 6). 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).

The mean tensile and shear strength at failure for both paints are listed in Table 1. Using a linear analysis, a Duncan's multiple range test of means shows significant (alpha $\leq$ 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 (shown by breaks in the underscores in Table 1). Load-deflection curves were plotted for all tests and visually analyzed. 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.

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

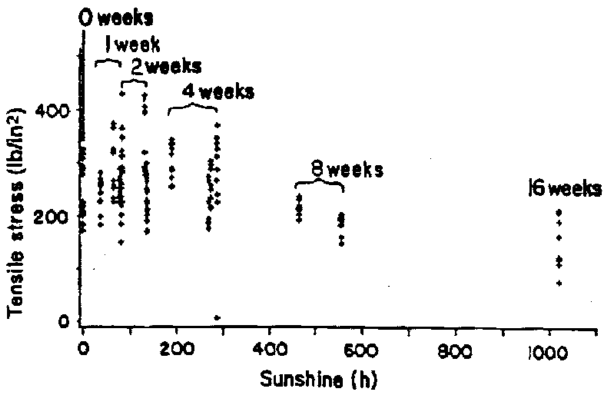

Figure 5. Ultimate tensile stress compared with sunlight exposure time of acrylic latex primer on western redcedar. All adhesive failures and cohesive wood failures are shown (1 kb/in^2 = 6.9 kPa). (ML 86 5259)

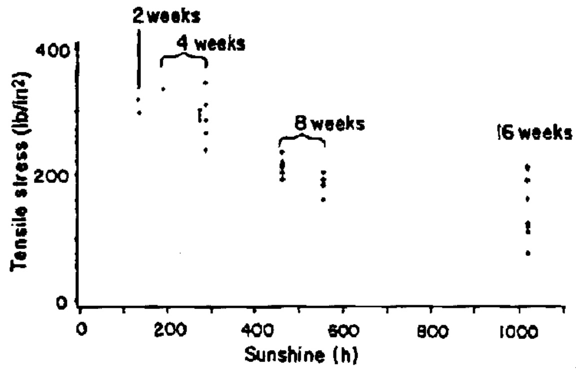

Figure 6. Ultimate tensile stress compared with sunlight exposure time of acrylic latex primer on western redcedar. Only primer/wood interphase failures are shown (1 lb/in2 = 6.9 kPa). (ML 86 5259)

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	2weeks	4weeks	8weeks	16 weeks	0	1 week	2weeks	4weeks	8weeks	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

specimens (Fig. 7). 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 from the controls but not different from the 1- and 2-week specimens (Table 1). The decrease in adhesion after 4 weeks of exposure is evident in Figure 8. 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 1). However, the trend was the same. As with the tensile tests, failures at the primer/EPI and the EPI/maple interphases were ignored and only results from specimens that failed at the wood/primer interphase were plotted.

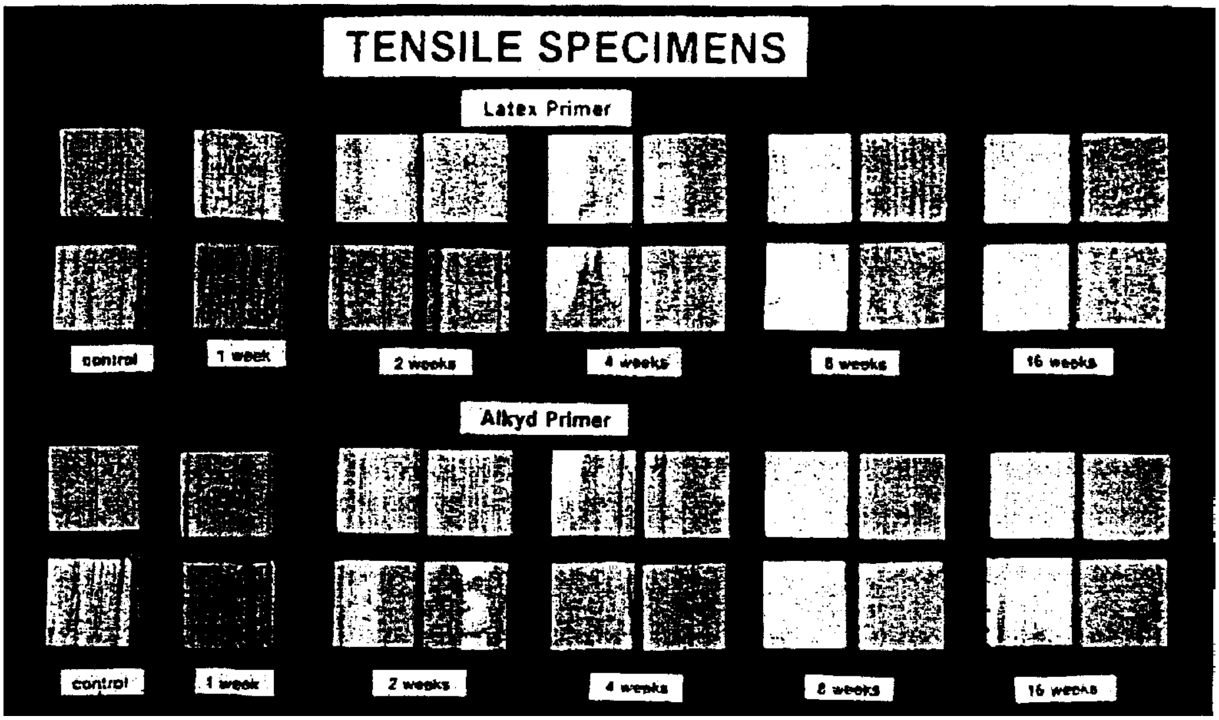

Figure 7. Failure surfaces of representative tensile specimens. (M86 0043)

Paint adhesion tests: oil primer

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 measurements for many specimens weathered 2 weeks or less reflected only wood failure and were deleted.

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. 7). 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.

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 more strongly to weathered latewood than did the latex primer.

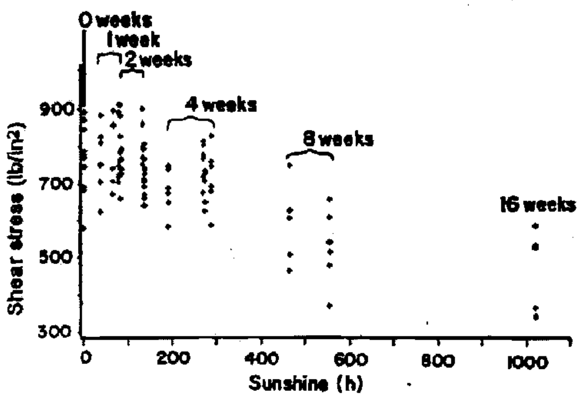

Figure 8. Ultimate shear stress compared with sunlight exposure time of acrylic latex primer on western redcedar. All adhesive failures and cohesive wood failures are shown (1 lb/in^2 = 6.9 kPa). (ML 86 5261)

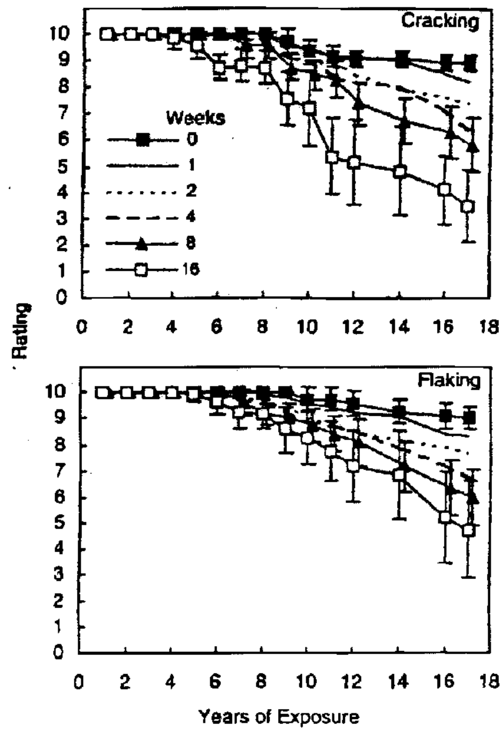

Figure 9. Paint evaluations for cracking and flaking during 17 years of outdoor exposure for specimens painted with a solventborne water-repellent preservative, one coat of alkyd-oil primer, and one coat of acrylic latex topcoat (WRP/alkyd/latex). The data points are the average of 12 observations, and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

Outdoor weathering of paint: cracking and flaking

The most notable differences among the finishes were found for cracking (ASTM D661) and flaking (ASTM D772). The effect of preweathering on these paint degradation mechanisms were evaluated for 17 years for the three different paint 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, boards painted with any of the three paint systems began to show cracking during the exposure period (Fig. 9). Flaking generally followed cracking after a year or two (Fig. 9). Differences in paint performance after 17 years of exposure for the different preweathering periods can clearly be seen in Figure 10. 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.

WRP/alkyd/latex paint system

The effect of preweathering can clearly be seen in the cracking and flaking evaluations during the 17 years. Boards with 16 weeks of preweathering began to show signs of cracking after only 3 years of

Figure 10. Exposure fence west of Madison, Wisconsin, showing painted specimens after 17 years of outdoor exposure (F2, WRP/alkyd/latex; F3, alkyd/latex; F4 latex/latex; numbers are weeks of preweathering).

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 photographs of the boards after 17 years of exposure (Fig. 11a-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 9, there is clearly a slight difference in performance between the 0- and 1-week preweatherings (Fig. 11a, 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 of a WRP pretreatment, one coat ofprimer, and one topcoat.

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. 12) than for the specimens with the same amount of preweathering finished with the WRP/alkyd/latex paint system (Fig. 9). This can be seen by comparing photographs of panels from the different paint systems preweathered for the same amount of time (Fig. 13a, b, c compared with Fig. 11a, b, 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. 12). For WRP-treated boards, flaking occurred about 1 to 3 years after cracking. However, for boards without WRP, flaking was immediately evident upon cracking.

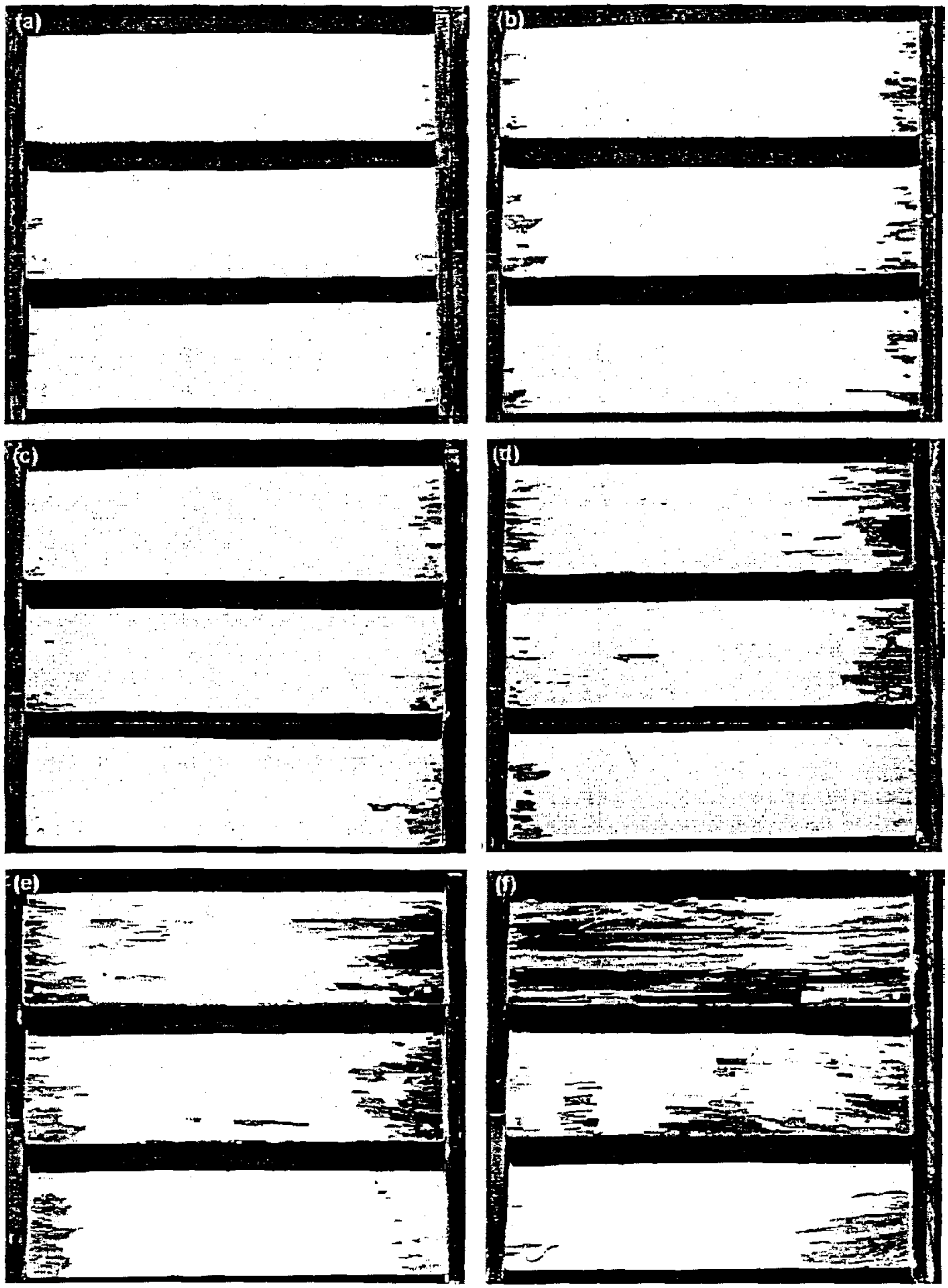

Figure 11. Examples of panels painted with a solventborne water-repellent preservative, one coat of alkyd-oil primer, and one coat ofacrylic latex topcoat (WRP/alkyd/latex) after 17 years of outdoor exposure. (a) control, no exposure prior to painting, (b) preweathered 1 week, (c) preweathered 2 weeks, (d) preweathered 4 weeks, (e) preweathered 8 weeks, and (f) preweathered 16 weeks.

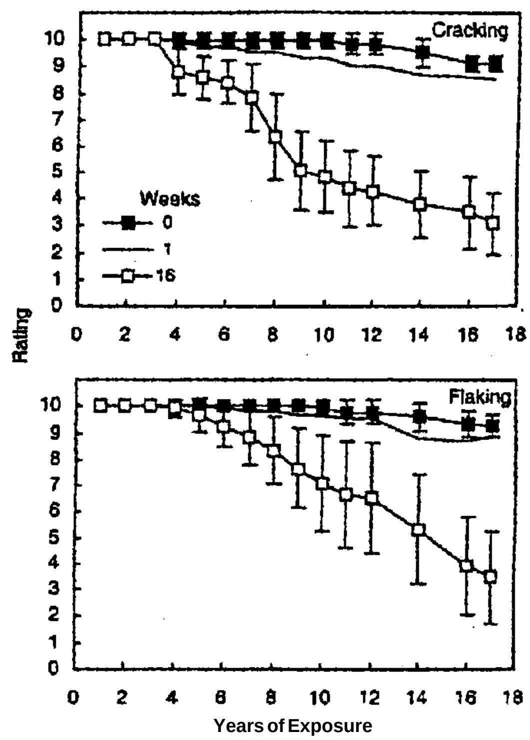

Figure 12. Paint evaluations for cracking and flaking during 17 years of outdoor exposure for specimens painted with one coat of alkyd-oil primer and one coat of acrylic latex topcoat (alkyd/latex). The data points are the average of 12 observations, and the bars give the standard deviation.

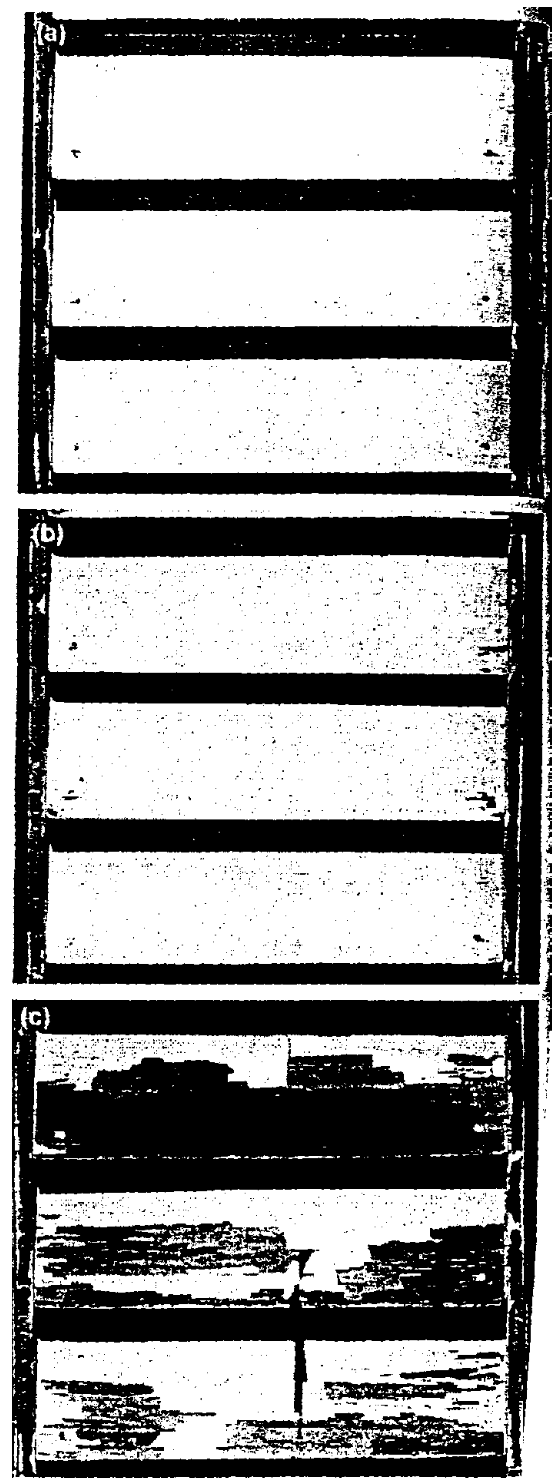

Figure 13. Examples of panels painted with a one coat of alkyd-oil primer and one coat of acrylic latex topcoat (alkyd/latex) after 17 years of outdoor exposure. (a) control, no exposure prior to painting, (b) preweathered 1 week, and (c) preweathered 16 weeks.

Latex/latex paint system

In general, ratings for the performance of the alkyd/latex paint system (Fig. 12) were slightly higher than those of the latex/latex paint system (Fig. 14). There was clearly a difference between the two paint systems within the 0-, 1-, and 16-week preweathering periods. Both the alkyd/latex (Fig. 12) and the latex/latex (Figs. 14 and 15) 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.

Paint adhesive strength compared with cracking and flaking evaluations

Figure 16 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 Figure 16c 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.

The paint adhesion study showed a link between paint adhesion tests and long-term performance of coatings, but it lacked sufficient data for reliability-based service life prediction (SLP).

Sealant Weathering

In 2001, we began a series of studies using reliability-based SLP to measure the degradation of sealants exposed outdoors. To obtain sufficient data for our analysis, two requirements were included in our test protocol. The first requirement for an SLP test protocol is to establish a meaningful link between the degradation observed in the laboratory and that from outdoor exposure. There needs to be a link between the dose of some degrading factor in the laboratory and the dose of this factor outdoors. For example, if UV radiation is a key cause of degradation, the radiation dose the specimens receive in the laboratory and outdoors must be measured. In the study of sealants, relevant weather parameters were measured and integrated with time to determine the dose that the specimens received. The second requirement of the test protocol is to find the appropriate material response to the dose. Load-deflection data (cyclic response) of the sealant were collected as the material weathered. These data enabled us to monitor

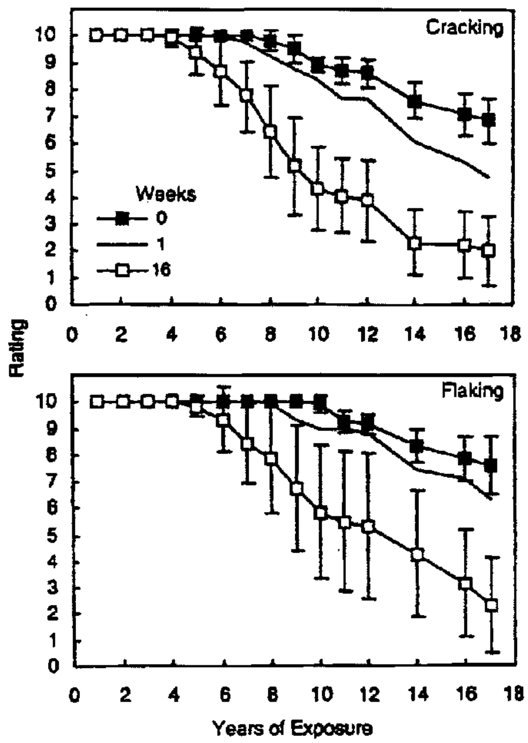

Figure 14. Paint evaluations for cracking and flaking during 17 years of outdoor exposure for specimens painted with one coat of latex primer and one coat of acrylic latex topcoat (latex/latex). The data points are the average of 12 observations, and the bars give the, standard deviation.

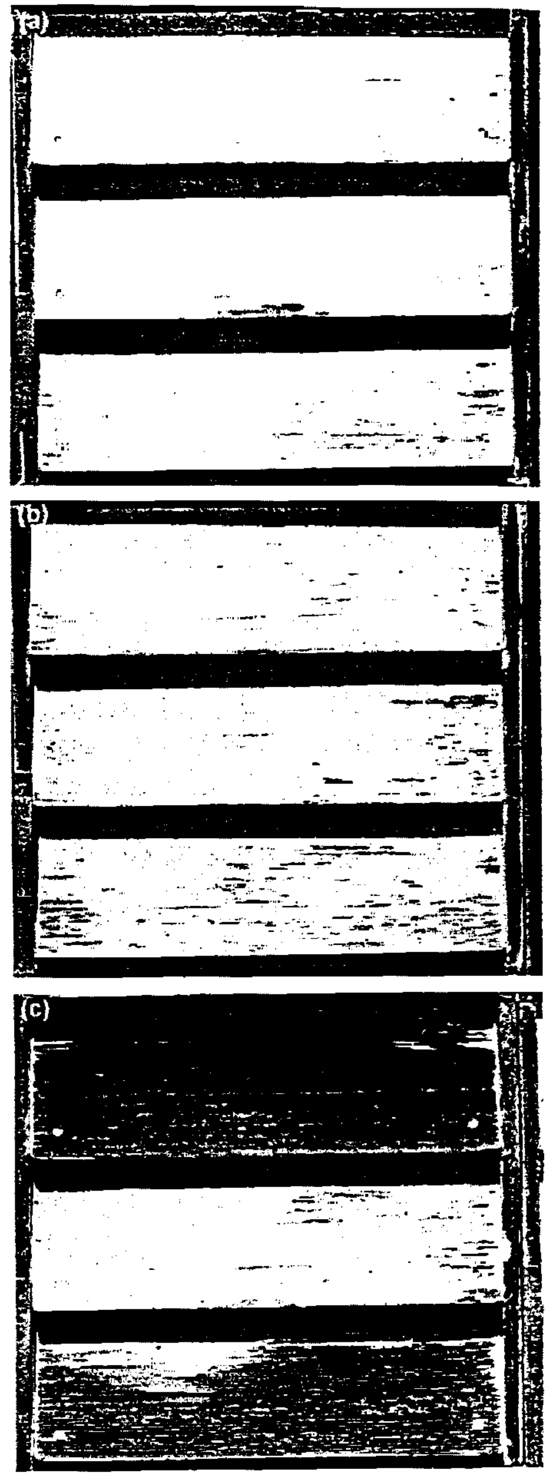

Figure 15. Examples of panels painted with one coat of latex primer and one coat of acrylic latex topcoat (latex/latex) after 17 years of outdoor exposure.
(a) control, no exposure prior to painting,
(b) preweathered 1 week, and (c) preweathered 16 weeks.

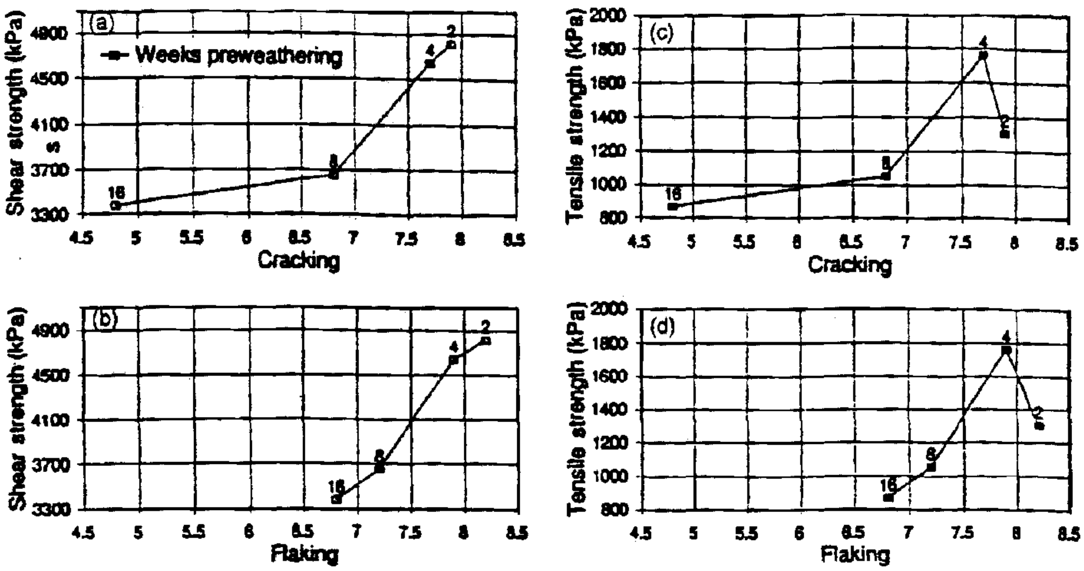

Figure 16. Paint adhesive strength (shear and tension) of the alkyd-oil primer compared with the cracking or flaking evaluations of the WRP/alkyd/latex paint system after 17 years of outdoor exposure. (a) shear strength versus cracking, (b) shear strength versus flaking, (c) tensile strength versus cracking, and (d) tensile strength versus flaking. The umber 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 R^2 values are 0.73 and 0.97, respectively.

changes in the stiffness of the sealant, detect adhesive and cohesive failures, and calculate the cumulative strain energy of specimens as they weathered. In an extended test, this information could be used to determine the exact conditions leading to the failure of the test specimen.

Daily Cycles

In a typical laboratory fatigue-cycle test, a mean stress, amplitude, and frequency are prescribed and the material is cycled to failure. In outdoor tests, the cycles are not characterized as easily. The daily cyclic changes are caused by changes in RH and temperature. The stress–strainresponse for individual specimens can be isolated from the data set for any specimen for any period of time during the exposure. For example, Figure 17 shows the stress–strainresponse for three specimens during a 4-day period. The specimens show a hysteresis as they go through diurnal cycles. The specimens were subjected to a cycle, but at a decreasing load and deflection on each of these days. Several consecutive days are shown, but the cycles were quite different for each day. In this case, the daily change in moisture content was superimposed on drying over several days. When the wood became wetter over several days, load/deflection increased with each daily cycle. Specimens also may undergo smaller cycles during a day (Fig. 18). These smaller cycles are caused by the complex interaction of the thermal response of the sealant and the moisture-induced response of the wood engine. It occurs primarily with the softer sealant formulations.

Seasonal Variation

The yearly fluctuation in temperature, RH, and UV radiation measured at the outdoor exposure site near Madison, Wisconsin, is shown in Figures 19 to 21. Figure 19 shows the weekly maximum, minimum, and running 7-day mean temperatures experienced during the exposure A similar plot for RH is shown

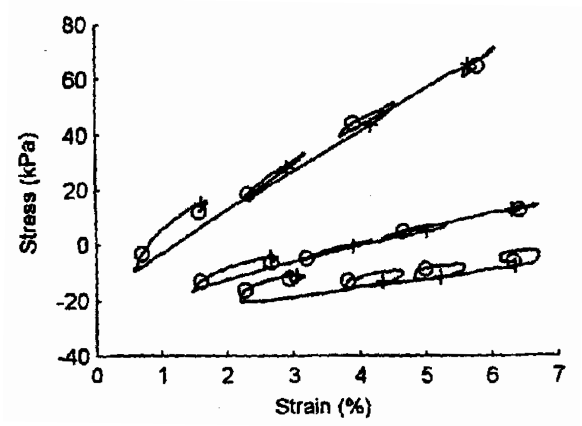

Figure 17. Stress-strain plot highlighting temperature-induced looping phenomenon. Three different sealant formulations are shown.

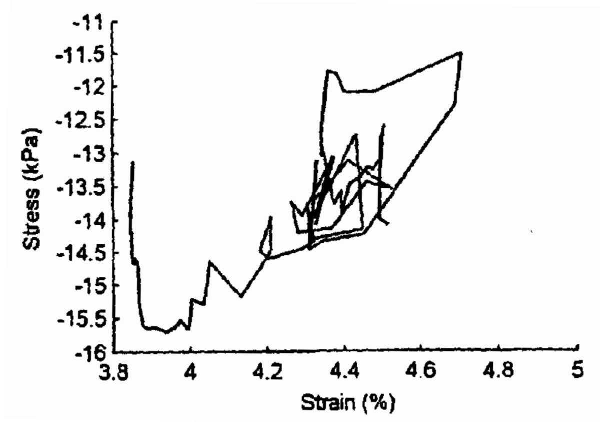

Figure 18. Stress–strain plot for one day of complex movement.

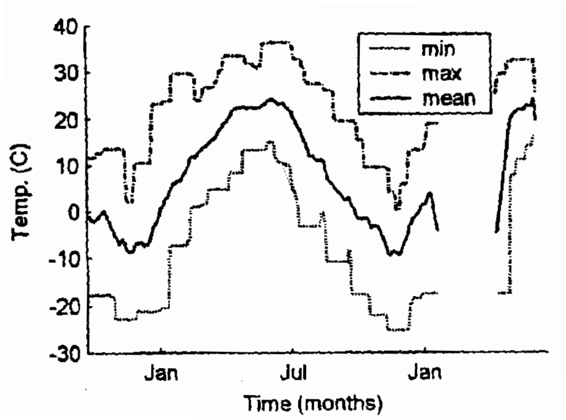

Figure 19. Yearly histogram of temperature. Maximum, minimum, and mean values are shown for week-long intervals.

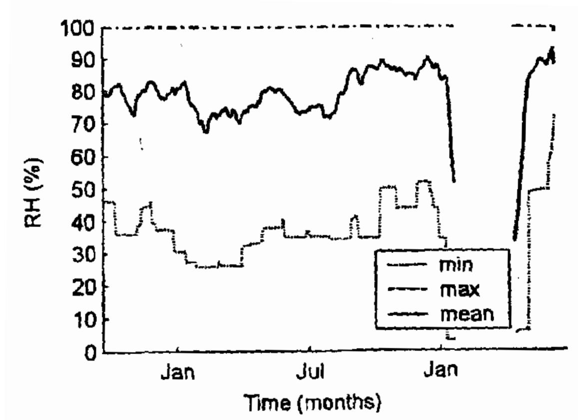

Figure 20. Yearly histogram of relative humidity (RH). Maximum, minimum, and mean values are shown for week-long intervals.

in Figure 20. It is interesting that RH always reached 100% at least once each week, probably during the night when the temperature was at the dew point. Figure 21 is a similar plot for UV radiation intensity. The UV irradiance for a year is shown in Figure 22. The peak height shows the total irradiance at 323.45 nm for each week.

Data Analysis

Figures 23 and 24 show the stress and strain for all specimens during 20 months for the TS apparatus. Figures 25 and 26 show stress and strain for all specimens during 16 months for the CS apparatus. The TS and CS apparatus were designed to give maximum–minimum strains of ±25%. However, these limits were exceeded several times during the exposure. The wood engine driving the cyclic movement gave almost the same strain on the different types of sealants (Figs. 24 and 26). The differences in the sealant formulations caused wide variation in the stress, which showed when all specimens were plotted (Figs. 23 and 25).

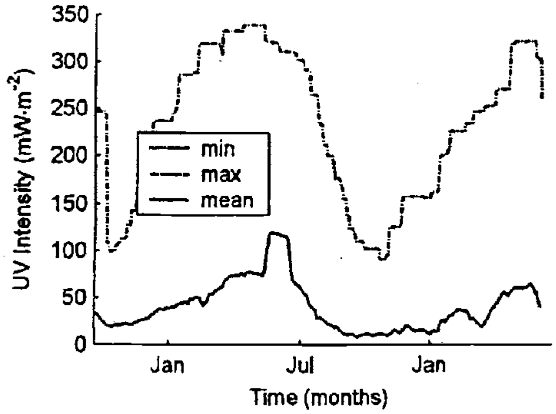

Figure 21. Yearly histogram of UV irradiance at 323.45 nm. Maximum, minimum, and mean values are shown for week-long intervals. (Minimum value lies along the 0 axis.)

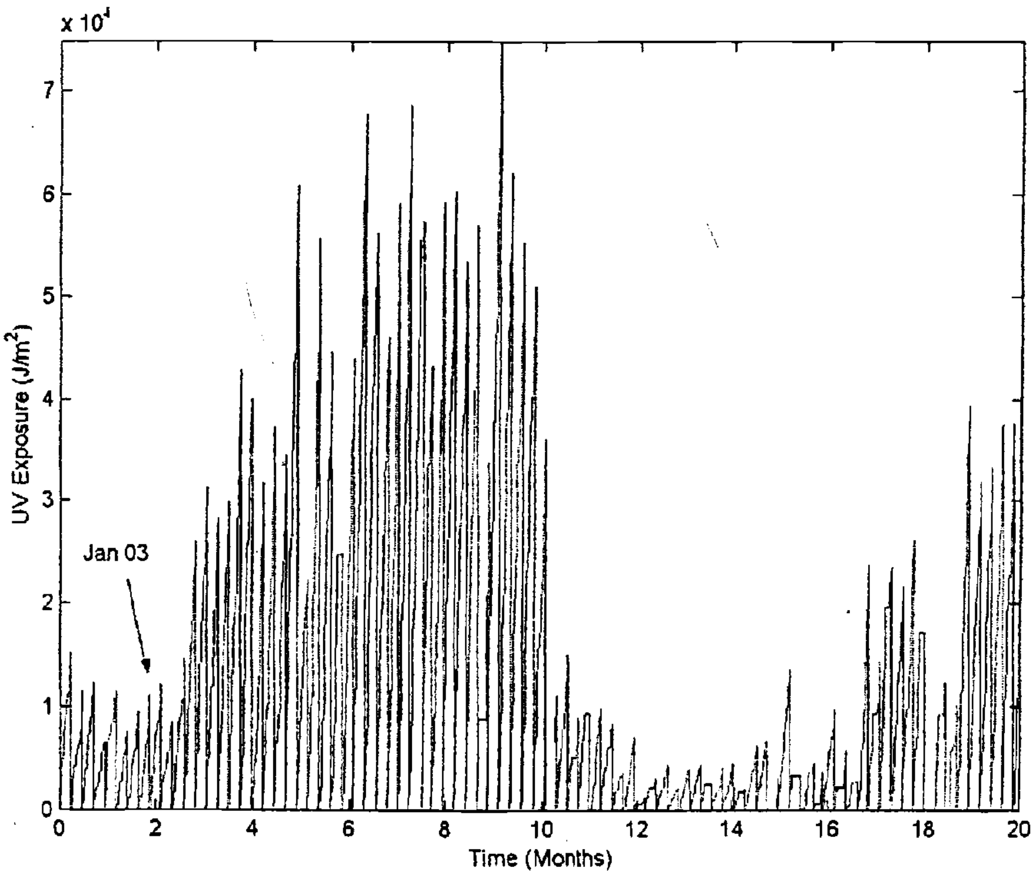

Figure 22. Weekly totals of spectral radiant exposure (J/m^2) at 340 nm.

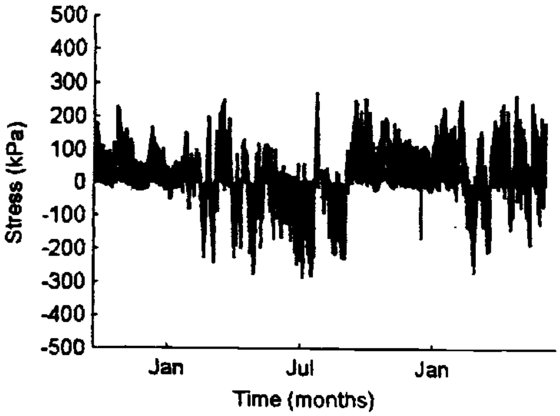

Figure 23. Stress as a function of time on CS-type apparatus for a 20-month exposure period.

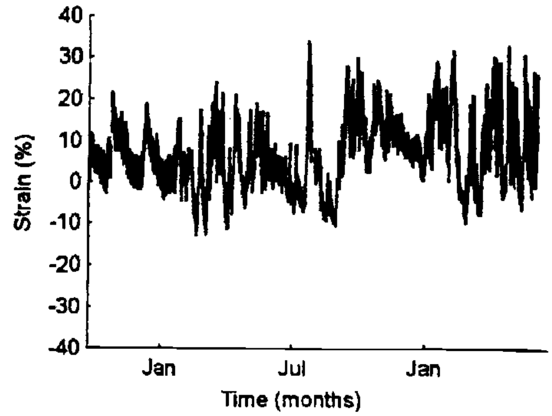

Figure 24. Strain as a function of time on CS-type apparatus for a 20-month exposure period.

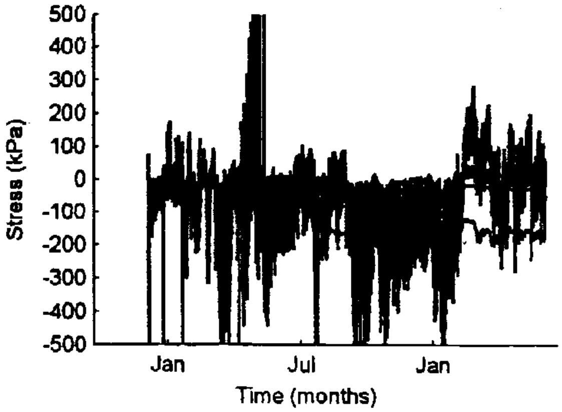

Figure 25. Stress as a function of time on TS-type apparatus for a 16-month exposure period.

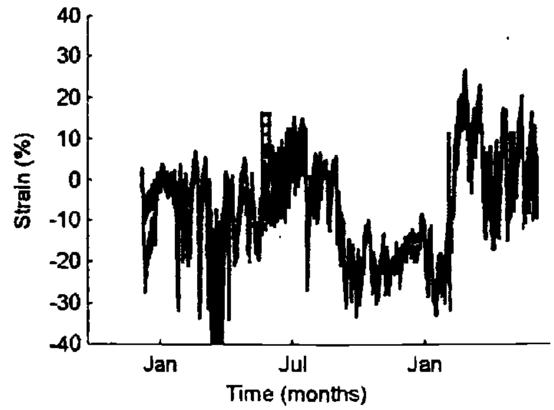

Figure 26. Strain as a function of time on TS-type apparatus for a 16-month exposure period.

Tests for Significance–Before beginning an exhaustive analysis of our data, we decided to apply some statistical tests to ensure that the data were nonrandom. For this purpose, we used a statistical tool called a normal value plot (NVP) (DeVor et al. 1992). An NVP measures data against a normal random distribution that has been scaled to match the extremes of the data. The straight-line portion of the NVP indicates variations in the data that are statistically random. The ends of the NVP that deviate from a straight line indicate nonrandom (deterministic cause and effect) variations in the data. Fortunately, our data were found to contain statistically significant variation. Figure 27 shows an NVP for the strain data from one specimen. We added a line at 45° for reference. From this figure, we can gather that the strain on this specimen is statistically significant-meaning that it is caused by an underlying deterministic physical process rather than random noise. We made similar plots for all our data, and all plots show the data to be significant.

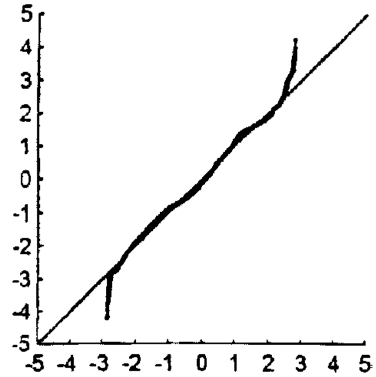

Figure 27. Normal value plot analysis showing statistical significance of our data.

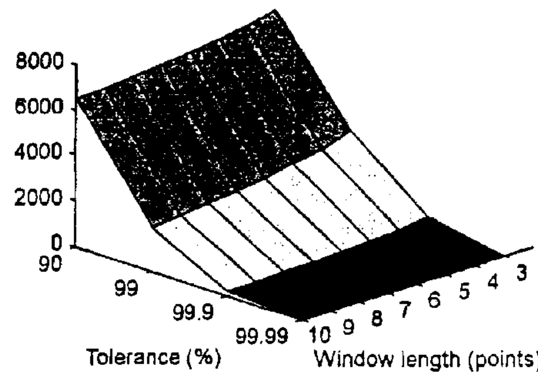

Figure 28. Analysis of data breakdown procedure. when selecting a fit to a given R^2 tolerance (on the x axis) using a given window length (on they axis), the z axis gives the number of points obtained.

Elastic Modulus –Our goal is to develop a cumulative damage model that will allow us to predict when sealants will fail. To do this, we need a measure of dose and a measure of performance. We developed dose measurements from the weather data. However, measurement of sealant performance is difficult. Our initial analysis involved using the load-deflection data to calculate the elastic modulus. We decided to use the elastic modulus as one measure of performance. We recognize that these are viscoelastic materials and do not give a true elastic modulus. However, we can obtain information on degradation using this method. We are developing methods based on cumulative stress and strain but have not yet completed our analysis.

Initial stress and strain rates play a role in the measurement of elastic modulus. However, their role seems to be smaller by some orders of magnitude than the role of temperature. We have the ability to select one exposure temperature and still have enough data to work with. Therefore, we selected all data collected at a constant temperature, in this case 20°C. We could have selected data at any temperature for which we had data (−20°C to +20°C). To obtain the elastic modulus, we can construct piecewise linear fits of the data.

We must consider two things in fitting the data. First, we must determine how many points to fit (that is, the width of the window). Second, we must determine how tight a fit is required before we trust it as an accurate model of what is really happening. Figure 28 shows the combined effect of these two analyses for all data from one specimen taken at 20°C. At a window width of 3 and R^2 = 90%, there are about 7000 segments; for a window of 10 and R^2 = 99.99% tolerance, there are almost no segments; for a window of 5 and R^2 = 99%, about half the data remain in the data set. In this analysis, there is no attempt to choose a type of cycle. Wider windows or tighter fits do obtain fewer outlying points, but they also discard a large number of points that we consider acceptable, Using the software we have developed, this same analysis can be done for all the specimens in just a few minutes.

Figure 29 shows the segments (modulus) for one specimen for 20 months. There is considerable spread in the data. This is caused by the segments being taken at different initial strains and different strain rates, both of which can affect the elastic modulus. The gaps in the data occurred during winter–spring when the temperature at our test site seldom reached 20°C. For this specimen, there was no apparent change in

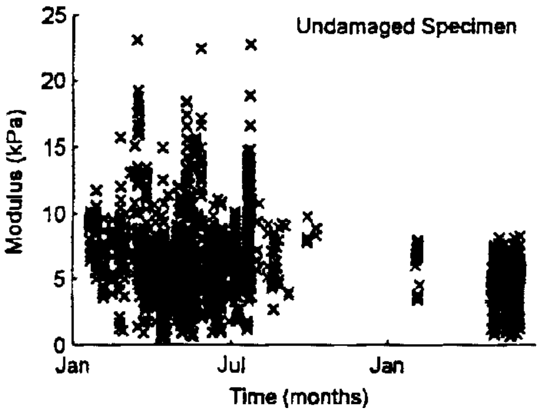

Figure 29. Approximated elastic modulus (R^2 > 99%, w = 4 fitting method) for an undamaged specimen.

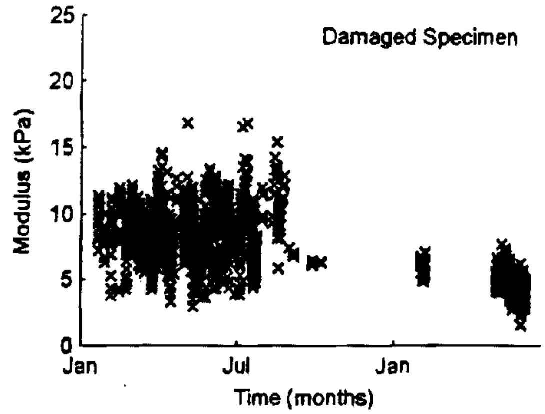

Figure 30. Approximated elastic modulus (using the R^2 > 99%, w = 4 fitting method) for a degraded specimen.

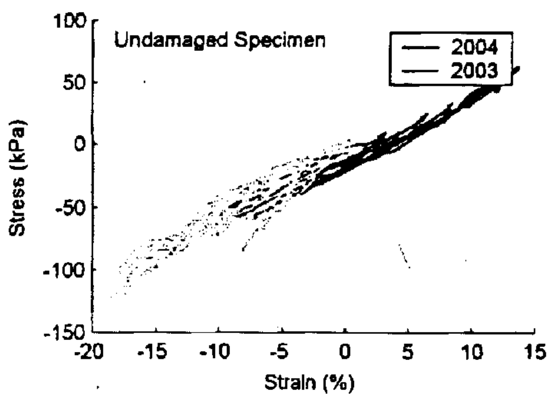

Figure 31. Comparison of stress-strain behavior of an undamaged specimen for 3-month periods in 2003 and 2004.

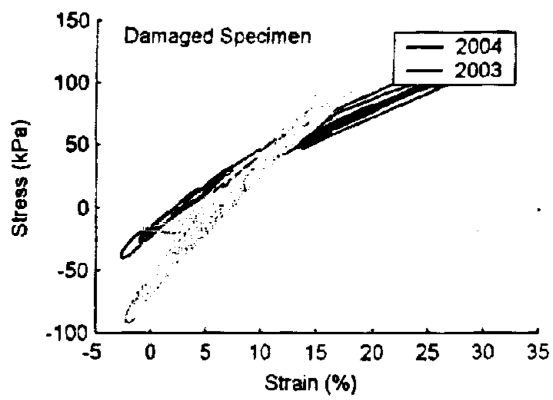

Figure 32. Comparison of stress–strain behavior of a degraded specimen for 3-month periods in 2003 and 2004.

modulus. If there was a change in modulus, a similar data treatment could show this-the specimen in Figure 30 shows considerable decrease in elastic modulus during the 20 months.

The change in modulus can also be determined by plotting stress–strain across selected periods at different times. Figure 3 1 shows the stress–strain plot for the same specimen as shown in Figure 29. The stress–strain plots are for April–June of 2003 and 2004; this specimen shows no change in modulus. The plots from both years have the same slope. Figure 32 shows the stress–strain plot for the specimen evaluated in Figure 30.

There was considerable change in the slope between the two years. The decreased slope (apparent modulus of elasticity) is caused by the opening of voids in the sealant and debonding from the substrate that resulted in a decrease in the effective cross-sectional area of the specimen (Figure 33). Similar undamaged specimens showed an increase in modulus during the same period, which was probably cause by additional curing or loss or solvent.

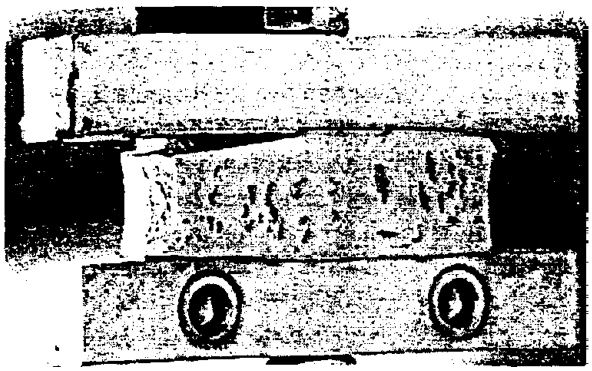

Figure 33. Close-up view of a degraded specimen.

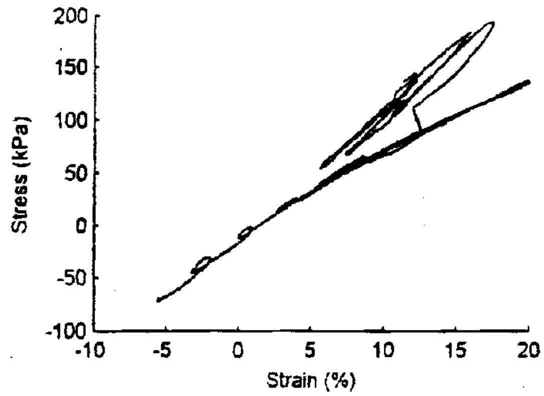

Figure 34. Sudden failure of a specimen. The change in slope occurred on 2004-05-12 at 14:27 CST. Ambient temperature was 19°C. Ambient RH was 45%. It had rained the previous day. The wood engine in the CS apparatus was in a drying cycle, which placed tension on the specimen.

By analyzing the data during the year, it is possible to determine whether the change was gradual, as might occur if the specimen degraded by polymer chain cleavage, or abrupt, as might occur if the specimen failed in adhesion or cohesion. Data analysis revealed that this specimen failed abruptly, and inspection of the specimen confirmed this (Fig. 33). The specimen failed both cohesively and adhesively. Review of the data can also reveal the time and conditions at which the failure occurred: Figure 34 shows several cycles with an abrupt change in the slope of the stress–strain plot. This abrupt change occurred at 2:27 p.m. on May 12,2004, following a day of rain.

We are continuing our investigations and exploring other methods for evaluating the data, such as cycles to failure, accumulated stress to failure, and accumulated strain to failure. These analyses would be improved by having stress response data from controlled strain experiments at various times during the exposure. This is not possible with apparatus in which the drivers are linked directly with the specimens. Dimensional change of the engines was directly transferred to the specimens, which makes it difficult to perform designed experiments that require some stressors to be turned off for some specimens. Unfortunately, engines that are either thermal- or moisture-driven (primarily wood and plastic) are subject to variability between engines because no two wood blocks or plastic tubes are exactly the same. Wood and plastic engines also tend to change as they age. This makes exact replication of experiments virtually impossible, not only between test apparatuses but within the same apparatus when multiple engines are used. Another disadvantage of this type of test apparatus is the difficulty of ensuring that the strain imposed on the specimens is of a specific amplitude about a prescribed mean value (zero in present experiments). Though the amplitude is determined by the size of the engines, material variability limits the precision with which the amplitude can be controlled. To center the strain about zero, specimens must be pre-strained at the time of installation to match the instantaneous state of the engines. Further, the mean dimensions of the engines change with seasonal variations in weather. Physical adjustment of the specimens is required to correct asymmetric strain. As our experience in using these wood engines increases, we expect reliability and control of precision and bias to improve.

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 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 adhesion test showed in a general way that weathering of the specimens prior to painting decreased paint service life.

Using a reliability-based service life prediction method, we demonstrated that the response of materials and the weather causing the response can be monitored continuously. The data can be analyzed to determine the elastic modulus of the material. Modulus change during exposure would indicate chemical change in the material. In addition, a small decrease in the load on the specimen could indicate loss of adhesion to the substrate or cohesive failure of the sealant. The occurrence of these types of changes can be linked to the weather causing the degradation, and changes can be evaluated in terms ofweather dose, not time of exposure.

We believe that reliability-based service life prediction models are superior to traditional field test methods. The instrumentation yields massive amounts of data that can be quickly analyzed while the tests are in progress. Early failures can be detected, differences in performance can be continuously monitored, and the linking of dose and response makes it possible to compare data from different tests. Our experience indicates that the response becomes independent of the time of the test or the time at which the test is started. The fundamental physical and chemical changes in the materials are measured and compared with measured stimuli causing the changes.

The up-front costs of instrumentation seem small in comparison to the benefits: complete history. of each specimen, timely evaluation of materials, comparison of results from different tests, quantitative materials response, and record of the weather.

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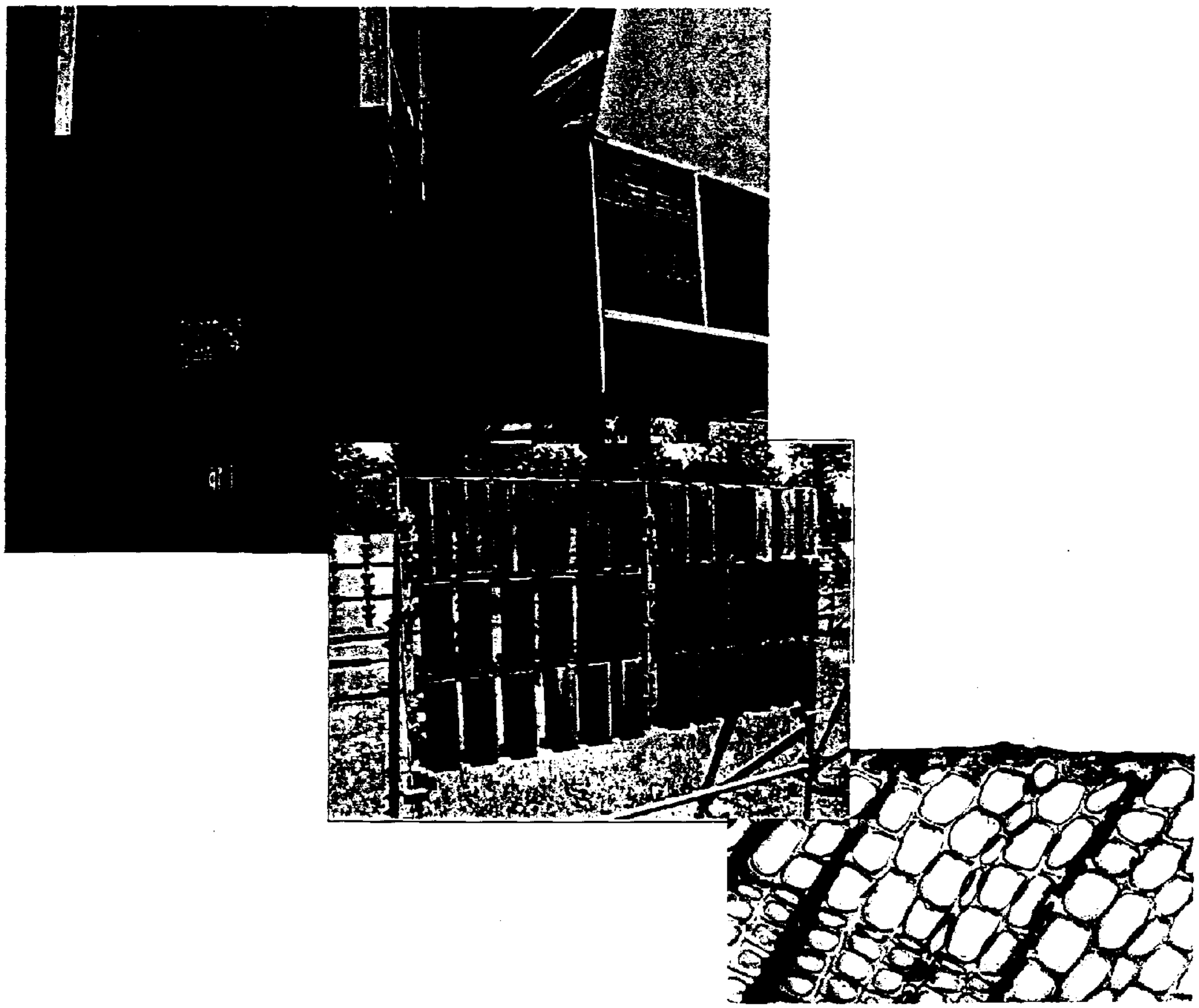

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