WOODCOATINGS

Foundations for the Future

Merging Weather Data With Materials Response Data During Outdoor Exposure

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Abstract

As part of an outdoor exposure protocol for a study of sealants, a full weather station was installed at the Forest Products Laboratory field test site near Madison, Wisconsin. Temperature, relative humidity, rainfall, ultraviolet (UV) radiation at 18 different wavelengths, and wind speed and direction are continuously measured. Using a specially designed apparatus, sealant specimens are subjected to weather-induced cyclic movement. The load-deflection information and weather data can be correlated to yield information on critical factors affecting the materials performance. This report describes the instrumentation of the outdoor test facility, the data collection system used for the study, and possible methods for analyzing the data. To establish a protocol for future work, two types of sealants (high and low modulus) were chosen for the initial phase of the work, to test the concept and to ensure that the specimen and weather data files could be accessed and manipulated. The results show a clear link between the materials response during weathering and the weather conditions causing this response. For the outdoor exposure used in this work, weather-induced cyclic fatigue of sealants and documentation of stress and strain during cyclic movement are critical aspects of the experiment.

Introduction

As part of ongoing work at the Forest Products Laboratory in Madison, Wisconsin, on the performance of materials used in residential construction, a study of sealants was begun in cooperation with the National Institute of Standards and Technology (NIST) (Gaithersburg, Maryland). This work involves detailed laboratory and field studies designed to develop service life prediction methods for sealants.

Service life prediction (SLP) is a term used by materials scientists to describe tests done rapidly to predict, with reasonable confidence, the performance that can be expected from a material in actual use. Other terms, such as accelerated aging, accelerated weathering, and artificial weathering, have also been used to describe these types of tests. The test is usually designed to simulate the normal failure mode of a material, but at an accelerated rate. For example, to accelerate the corrosion of painted steel, specimens are subjected to a test involving a salt water spray (ASTM B 117, ASTM 2001). Polymeric materials are often tested with devices to accelerate degradation catalyzed by UV radiation.

Accelerated weathering has generally focused on duplicating the effects of UV radiation and water. UV radiation from a carbon arc (ASTM D 822, ASTM 2001) was used in early weathering devices; to a great extent, this source was later replaced by a xenon-arc source (ASTM D 5031, ASTM G 26; ASTM 2001). Other devices use UV fluorescence light sources (ASTM G 53, ASTM D 4587; ASTM 2001). Considerable effort has been made to develop a light source that duplicates natural light and to replicate various other environmental conditions that accelerate degradation yet match the type of degradation that occurs outdoors.

General guidelines for accelerated testing of sealants is 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 performance. A sealant test that combines cyclic stress (fatigue), water immersion, and temperature change was initially developed by A. 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 used to induce cyclic movement (fatigue) of sealants during exposure. These devices generally use thermally induced dimensional change to generate fatigue in a sealant. 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).

In reviewing the work done in our laboratory and similar work reported by others who have developed accelerated test methods, two problems became obvious. First, weather is not consistent from day to day, season to season, year to year, and century to century (Martin 2002). How, then, can a reasonable test protocol be developed that simulates a weather environment? Second, weather data have not been used in any meaningful way during outdoor exposure. That is, there has been no link between specific weather events and response of materials to these events. For example, in previous exposure studies of the performance of coatings on wood substrates, weathered specimens were evaluated yearly (ASTM D 661, D 662, and D 772; ASTM 2001). Thus, a variety of weathering events that may have had a dramatic influence on degradation were averaged out. There was no way of knowing what the conditions were when the specimens degraded. The specimens may have degraded more or less at the same rate since the previous evaluation, or all the degradation could have occurred during a single weather event, like a hailstorm. Are periodic evaluations useful for determining the conditions that lead to failure? Accelerated tests have often given misleading results with some materials because critical factors causing the degradation were either not known or not measured.

Our approach to these problems is to instrument and measure both accelerated laboratory tests and outdoor tests. The materials response and the conditions in the laboratory test can then be compared with the weather data and the materials response obtained from the outdoor exposure. Quantifying and controlling the accelerated tests is being done at NIST, while monitoring the weather and quantifying its effects on the sealant during outdoor exposure is being done at the Forest Products Laboratory. At NIST, devices will be used to subject materials to known conditions in reproducible ways, to measure these conditions, and to measure the materials response during the exposure. The Forest Products Laboratory field site, which is 15 km west of Madison, Wisconsin, has been fully instrumented to collect weather data during outdoor exposure. This includes temperature, relative humidity, precipitation, and UV radiation. We report here the materials response of two different sealant compounds during approximately 2 months of weathering.

The focus of this report is to describe the instrumentation of the outdoor test facility, the data collection system used for the study, and possible methods for analyzing the data. The results show a clear link between the materials response during weathering and the weather conditions causing this response. We believe this technology is relevant to all types of materials research in which a laboratory test is to be used to predict performance of a material used in other environments, usually outdoors.

Experimental

Equipment

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): 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.

Data from the UV radiometer are collected by the SERC srl8acq.exe program. As the program is running, it updates a file containing the average intensity over the last minute. The 1-min average data are saved in a temporary tab-delimited file. A 12-min average of this file is stored in an ASCII fixed-width database, then forwarded to SERC for inclusion in the national database. The UV data for inclusion in the local database is extracted from the 1-min file simultaneously with the other data (mechanical measurements, temperature, relative humidity, etc.).

The radiometer is located on a tower 4 m above the ground, and, except for some trees located 200 m away, the view of the horizon is unobstructed in all directions.

Weather Station

Weather data are collected using a Texas Weather Instruments WRL-25 logging weather station (Texas Weather Instruments, Dallas, Texas, USA). The software that collects data from the weather station is WeatherView32 (Weather View, Inc., Amity, Oregon, USA). Data are stored locally in a tab-delimited database as hourly averages; however 1-min data are extracted for use in our calculations.

Test Apparatus

The test apparatus subjects the specimens to controlled 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 changes in relative humidity (RH) or from precipitation. The wood moves against an aluminum frame to produce a cyclic movement. All other parts of the apparatus are stainless steel. A small amount of movement is also achieved from the thermal expansion and contraction of the aluminum part of the apparatus. This movement is opposite the moisture-induced movement in the wood and thus gives a slight increase in the overall deflection of the specimens as the weather changes. As most movement was achieved from the movement of the wood as it changed moisture content, we will refer to the blocks of red oak as the “wood engine.”

Small holes were drilled in the wood engine to accelerate the wetting and drying of the wood, thus increasing the amount of deflection in a given interval. The end grain of each block of wood was sealed with primer paint to minimize end-grain checking. A test apparatus capable of attaching 10 specimens is shown in Figure 1. Three panels of red oak cause the distance between the steel bars at the top and bottom to cycle as the wood moisture content changes. The aluminum is attached to the bar at the top; the load cell and specimen are uni-axial and are connected using a stainless steel threaded rod with locking nuts. Each specimen is fitted with a linear variable differential transformer (LVDT). Only four LVDTs are shown in Figure 1.

The LVDTs are used to measure specimen deflection. These LVDTs are hermetically sealed sensors (HSD-750, Macro Sensors, Pennsauken, New Jersey, USA) with a deflection of ±6.35 mm. Force transducers (load cells) are used to measure the load in the system. The environmentally sealed transducers (Model SSM-AJ-250, Interface, Scottsdale, Arizona, USA) have a capacity of ±113.4 kg.

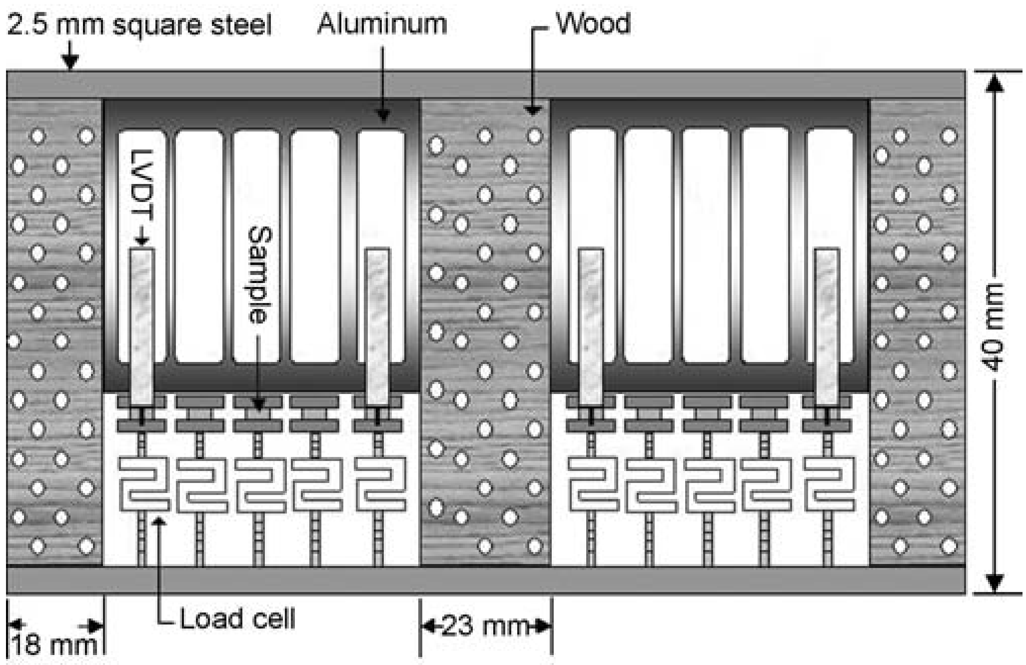


Figure 1—Schematic of sealant test apparatus.

Data Acquisition

Data from the force transducer and LVDT are fed into a Keithley 2700 Data Acquisition system, using Keithley 7708 voltage measurement expansion cards (Keithley Instruments, Cleveland, Ohio, USA). The field site and main laboratory are linked by computer.

Data collection is performed using a custom program written in LabView. This program periodically collects voltage measurements from the Keithley system, and 1-min averaged data from the SR-18 and the WRL-25. 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 database.

> Note: We aren’t directly using the SR-18 or the WeatherView32 database. Rather, every time we collect a point, we capture the latest minute-average of UV data and Weather data. This gives us a much finer mesh of points, which tracks more accurately with the force/deflection measurements than we could get otherwise. By “tracks accurately” we mean that all the different types of data are measured at the same time.

The data collection rate varies depending on the rate of movement of the specimens. During periods of rapid movement, more data are collected. As the movement of the specimens slows, the rate of data collection slows. During periods of rapid movement, a point is collected every 15 s, and 10 points are averaged to obtain a measurement (2.5-min average). At the other extreme, a measurement is collected every 150 s and 10 points are averaged to obtain a measurement (25 min average). The collection rate within these extremes is determined as follows:

Before collecting any points, the program checks to make sure that the sensors have power. To do this, we dedicate two channels on the Keithley to measuring sensor power. If power is not sufficient, a point is not taken. After each point is collected, the program queries the Keithley to ensure the data are within an expected range. If so, the point is saved. Otherwise, the point is discarded and another collection attempt is made. After each measurement (1 0 point average) is collected, the maximum rate of change for all samples between measurements is computed. If this rate exceeds an assigned tolerance, the time delay between readings is increased. If the rate is lower than the tolerance, the time delay between points is decreased.

There are about 5 min of battery back-up power for the sensors, and about 20 min of backup for the computer. If there is an extended power outage, the computer automatically reboots when power is restored.

Materials

Two types of sealants were chosen for the initial phase of the work, to test the concept and to ensure that the specimen and weather data files could be accessed and manipulated. The intent of this research was not to evaluate the performance of sealants that would be used in residential construction, but to establish a protocol for future work. Therefore, a high modulus sealant and a low modulus sealant were selected to give different load–deflection characteristics.

Methods

Data from the specimens was analyzed using Matlab 6.1 R12, a numerical mathematics package. Specimen response was measured for approximately 2 months. During this period, some specimens failed during an unusual weather event.

Results and Discussion

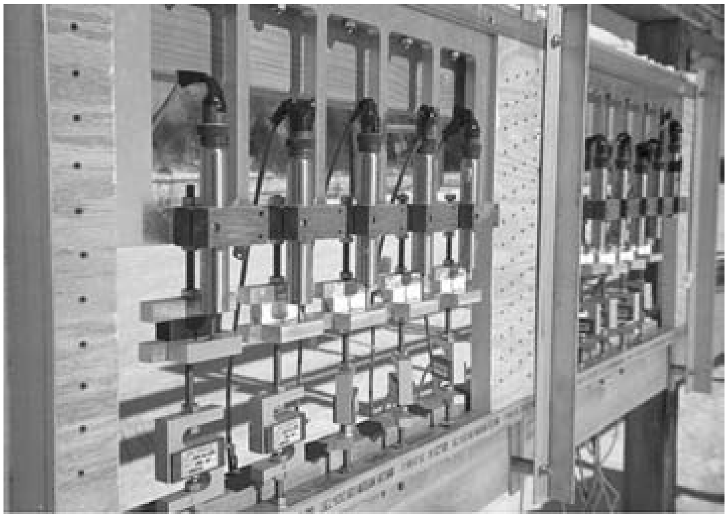
The first challenge for an SLP test protocol is to establish a meaningful link between the degradation or damage observed in the laboratory outdoor exposure. There needs to be a link between the dose of some degrading factor in the laboratory and the dose of this factor outdoors. For example, if UV radiation is a key cause of degradation, the dose of radiation the specimens receive in the laboratory and outdoors must be measured. In the work described here, relevant weather parameters were measured and the data were integrated over time to determine the dose that the specimens received. (For example, we know the total dose of UV radiation at the 18 different wavelengths.)

The second challenge of the test protocol is to find the appropriate material response to the dose. For this work, the load-deflection data (cyclic response) of the sealant were collected as the material weathered. These data enabled us to determine the stiffness of the sealant as it weathered. In an extended test, this information could be used to determine the exact conditions leading to the failure of the test specimen.

Sealants used in conjunction with glass, metals, and masonry are placed in compression as these materials expand with an increase in temperature, and they are placed in tension as they cool. When the sealant is in contact with wood, a change in temperature has the opposite effect. An increase in temperature causes the RH to drop and the wood shrinks, placing the sealant in tension. In addition, a change in RH, even without any change in temperature, can cause extremely large changes in dimension. For this reason, a wood engine was chosen to cause the cyclic movement for the outdoor tests. Movement in wood components is caused primarily by changes in the moisture content of the wood.

Two types of apparatus were developed. In one, the wood engine produced movement of the specimens in the same way as a non-wood substrate; that is, tension, with increased RH. This apparatus was designed to simulate the designs previously used, but to be driven primarily by changes in RH, not temperature. The second design works just the opposite. An increase in RH places the specimen in compression. Only data from the first type of apparatus are included in this report.

The wood engine was designed such that changes in wood moisture content in the range of about 6% to 20% would cause about 6.4 mm of change in the sealant. This was thought to be a reasonable working range for the Madison, Wisconsin, weather conditions and would give about ±3.2-mm change in dimension to the sealant specimens (about ± 25% strain). Wood exposed outdoors goes through a yearly cycle; in the winter, its moisture content is higher (wood is more swollen) than in the summer (less swollen). Diurnal cycles and weather events are superimposed on this yearly cycle. Even though the amount of water in the air is low during the winter, the air is often close to the dewpoint and the RH is therefore high. Because wood is in a more swollen state during the winter, the specimens cycled in tension through out the test.



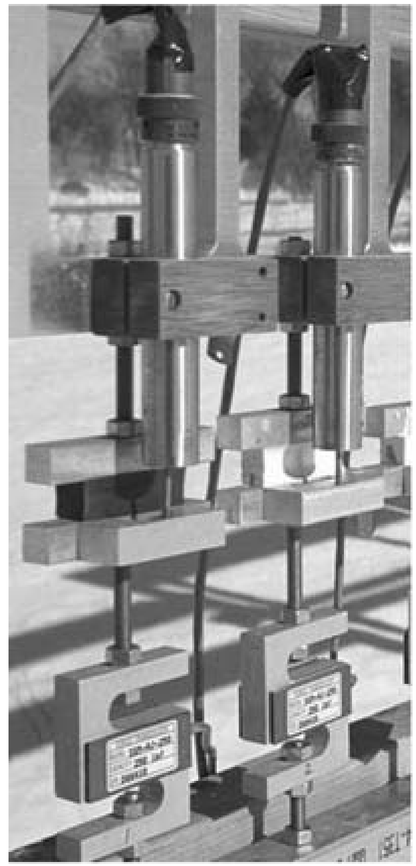


Figure 2—Sealant test apparatus showing 10 specimens in test (above),

Figure 3-Close-up view of sealant holder, sealant, LVDT, and load cell (right).

This would not be the case during the summer. In summer, the wood would be in a drier condition and this would put the specimens in compression. During the spring and fall, the cycles would involve both tension and compression.

The specimens were tested for 2 months (December 2001 to February 2002) and are shown installed on the test fence (Fig. 2). Figure 3 shows a close-up view of the LVDT, load cell, and different types of sealant.

Figure 4 shows the strain of two specimens during outdoor exposure. The wood engine driving the cyclic movement gave almost the same strain on the different types of sealant. The daily cyclic changes indicate the movement caused by changes in RH and temperature. Note that the rate of increasing and decreasing strain is not the same.

This is most obvious from day –10 to day 2 (0 corresponds with January 1 , 2000). The sealant went from 3% to 23% strain on day –10, then cycled back to 8% on day 2. This type of nonsymmetric behavior is typical of what would be expected with sealants used in conjunction with wood construction. Wood absorbs moisture much quicker than it releases it during drying. Drastic changes in strain such as occurred on December 15 (day –16) and February 18 (day 49) were a result of rain, which quickly increased the length of the wood engine and therefore placed the sealants in greater tension. The rainbow on February 18 to 20 (days 49 to 51) was very heavy and thus resulted in high increases in strain in the sealant. This turn of events was not expected.

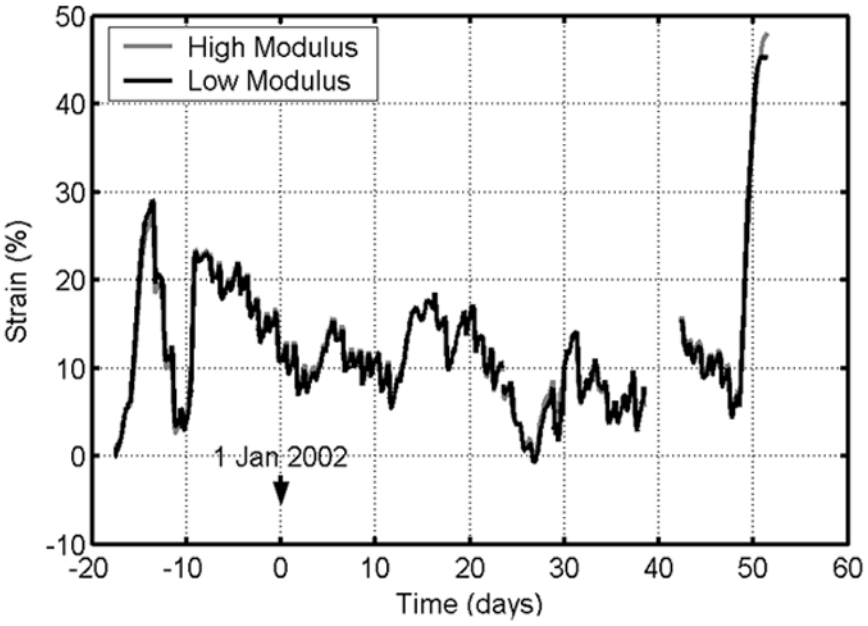


Figure 4—Strain as a function of time for high and low modulus samples. On the abscissa, positive values indicate tension, negative values indicate compression. The apparatus is so designed that strain is the same for all specimens, shown by the almost identical plot for the two samples. The computer system was down for 5 days for replacement of components and reconfiguration, which caused the gap in data beginning on day 38.

The wood engine had been operating within its design parameters throughout the winter and was keeping the specimens under tension with strains of 5% to 25%. Then, rain fell for 3 days. This weather event, unusual for winter, caused some specimens to fail in adhesion to the aluminum substrate. The data collection system was functioning during this time, and failure of the specimens was readily apparent (Fig. 4).

Figure 5 shows the same data for January 10 through January 30 (days 10 to 30), along with relative humidity. Any other weather data (e.g., temperature, rainfall, UV radiation) could also have been plotted. The response of the sealant test-apparatus to the change in relative humidity can easily be seen - the specimens showed increased tensile strain during periods of increased relative humidity. Diurnal changes in RH resulted in small changes in strain in the sealant.

The large difference in stiffness between the two sealant samples can be seen in the difference in stress (Fig. 6). As with strain, diurnal changes can be observed for stress. Rain and snow caused large changes in stress and strain in the sealants.

Exposure of the sealants to UV radiation, cycling, temperature, and moisture over a long term (several years) should result in changes in the sealant that can be monitored by tracking its stress/strain behavior. To illustrate how this can be done, the stress/ strain behavior of the two types of sealants is shown in Figure 7. Since the moisture content of the wood engine was high, both sealants were in tension throughout the period of observation. All the data are shown in Figure 7 and the stress/strain values are superimposed. The plot can be simplified by selecting data in a defined temperature range. Figure 8 shows this for a temperature of −18± 0.5°C.

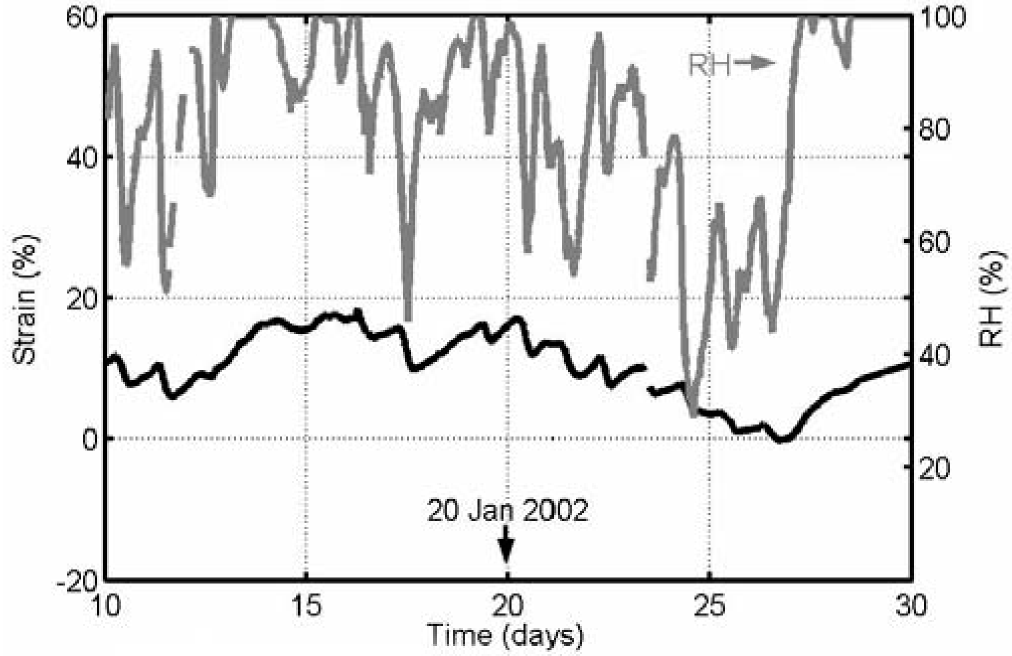


Figure 5-Strain as a function of time for the multiple fixture in outdoor testing, along with relative humidity. On the abscissa, positive values indicate tension, negative values indicate compression. Only the period from day 10 to 30 (January 10 to 30) is shown.

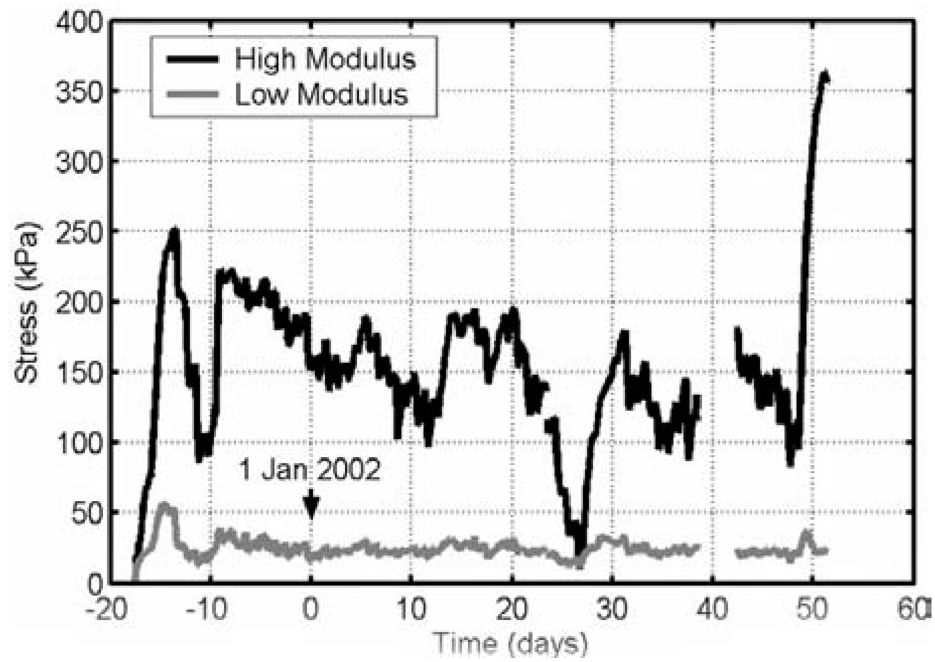


Figure 6-Stress as a function of time for high and low modulus samples. On the abscissa, positive values indicate tension, negative values indicate compression The computer system was down for 5 days for replacement of components and re configuration, which caused the gap in data.

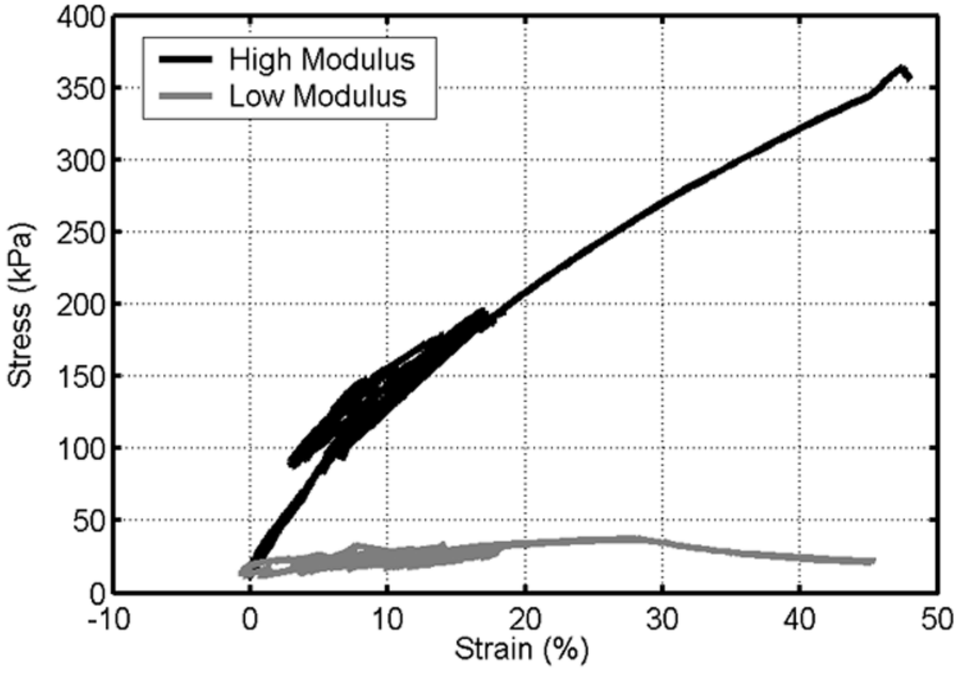


Figure 7 — Stress versus strain plots for high and low modulus specimens over the 2-month exposure period.

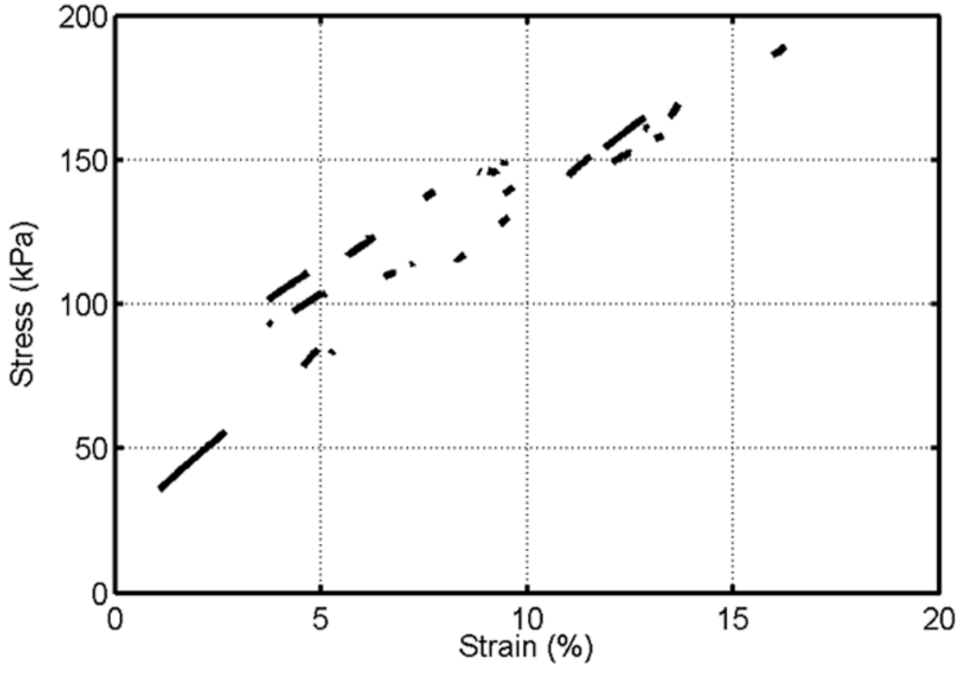


Figure 8-Stress versus strain at −18°C ± 0.5°C for a high modulus specimen.

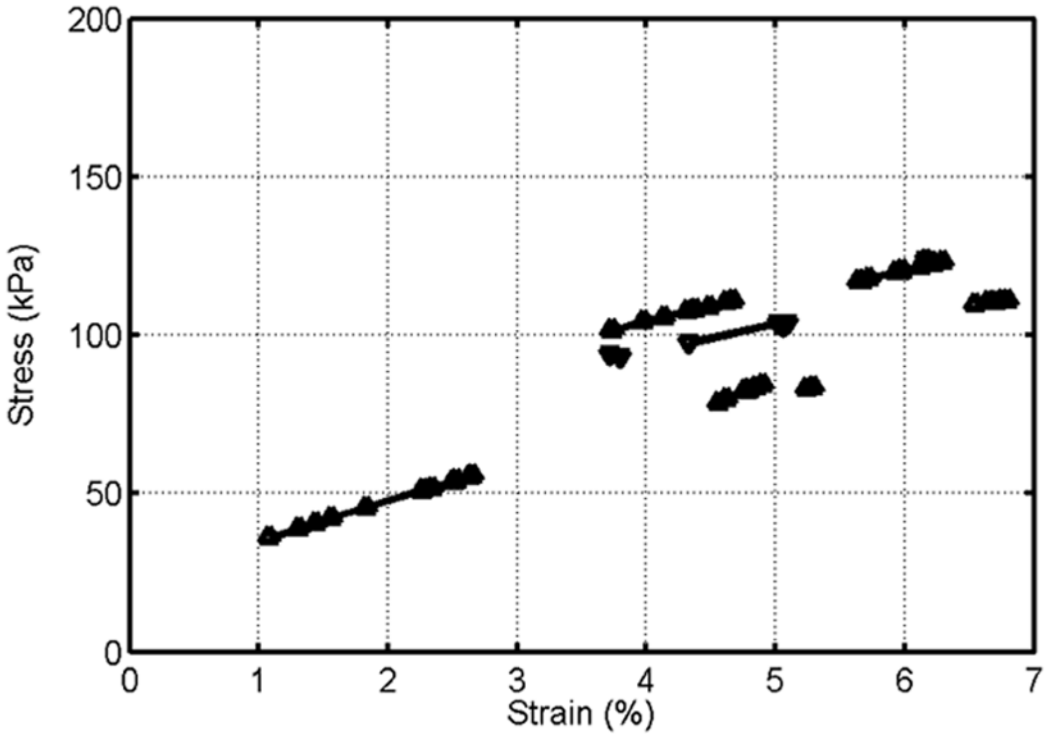


Figure 9-Stress versus strain plots selected for −18°C ± 0.5°C and 0 to 7% strain.

By further selecting for a certain initial strain, stress/strain plots can be isolated and analyzed (Fig. 9). These plots show no change in stiffness for the test material during the duration of the test. This particular polymer showed no change for the short duration of this test period. Had there been a change in the stiffness of the sealant over time, this could have easily been detected with this analysis. Hypothetically, aging of the specimen could either cause additional cross-linking within the material (thus causing an increase in stiffness) or chain scission (thus causing a decrease in stiffness). Other ways of analyzing the data are being investigated.

Conclusion

A methodology for measuring the material properties of sealants during outdoor testing was developed. By measuring the sealant response during all weather conditions, critical factors that affect degradation of the sealant specimens were determined. As an example of how the data can be processed, the stiffness of the specimens at various times during the exposure was determined. Since the stiffness of these types of viscoelastic materials changes with temperature, data at a particular temperature can be isolated and the material properties can be compared. For the outdoor exposure of the sealants used in this work, weather-induced cyclic fatigue of specimens and the documentation of stress and strain during this cyclic movement were deemed to be critical aspects of the experiment. Information on critical weather events was necessary for observing and interpreting the degradation. For other types of materials, different measurements might be important.

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