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Predictive Service Life Tests for Roofing Membranes

Phase II Investigation of Accelerated Aging Tests for Tracking Degradation of Roofing Membrane Materials

David M. Bailey, Carl G. Cash, and Arthur G. Davies, Jr. September 2002

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Foreword

This research was conducted for the Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 40162784AT41, "Military Facility Engineering Technology"; Work Unit CFM-A322, "Innovative Roof Investment Methodologies." The technical monitor was Albert Young, CECW-EI.

This work was performed by the Materials and Structures Branch (CF-M) of the Facilities Division, Construction Engineering Research Laboratory (CERL). The Principal Investigator is David M. Bailey. A portion of this work was performed under contract by Carl G. Cash, principal engineer and chemist, and Arthur Davies, laboratory manager and chief staff engineer, with Simpson Gumpertz and Heger, Inc., of Arlington, MA. Martin J. Savioe is Chief, CEERD-CF-M, and L. Michael Golish is Chief, CEERD-CF. The Technical Director of the Facility Acquisition and Revitalization business area is Dr. Paul A. Howdyshell, CEERD-CV-ZT. The Director of CERL is Dr. Alan W. Moore.

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1 Introduction

Background

The U.S. Army and the roofing industry have extensive field experience with roofing membranes. With Unified Facilities Guide Specifications (UFGS) available for bituminous built-up roofing (BUR), ethylene-propylene-diene terpolymer (EPDM), poly [vinyl chloride] (PVC), and modified bitumen (MB) roofing systems, the Army currently uses these materials on all types of low-slope applications. Even when the guide specifications are carefully adhered to, however, the average service life of the Army's low-slope membrane roofs is estimated to be considerably less than the industry-presumed 20-year design life (Bailey 1999).

Roofing manufacturers continually change the composition of their membrane products, and they introduce new materials at an increasing pace. These changes are often made to reduce manufacturing costs, or to remain competitive with new offerings from competitors, or to address performance problems reported about materials in service. These new and reformulated materials may not be thoroughly researched or field-tested before they are brought to market. Despite the initial satisfactory ratings for some of these products when newly installed, their long-term durability is unknown.

Federal procurement regulations prohibit the Army (and other government agencies) from specifying roofing systems or components by product name. Instead, the regulations mandate that roofing membranes be specified by generic type and that these generic types meet the appropriate ASTM* standards. However, these standards do not adequately address the durability of the material in service because there are essentially no data available on physical tests before, during, and after weathering. Consequently, as contractors compete to reduce delivery costs, they

* ASTM: ASTM International, formerly the American Society for Testing and Materials.

may provide untested, inferior membranes in place of ones that have demonstrated satisfactory long-term in-service durability.

As part of its facilities acquisition and revitalization mission for the U.S. Army Engineer Research and Development Center (ERDC), the Construction Engineering Research Laboratory (CERL) is developing methods for predicting the long-term performance and expected service life of roofing membranes. Predictive service life tests, which comprise both a property-measurement test and an accelerated aging test, can be completed within a matter of weeks to provide both a measure of the absolute durability of a specific product and means to compare the relative durability of alternate products for a given application. These predictive testing procedures will help Army roofing managers make better-informed material-selection decisions, and will promote the procurement of quality roofing products for Army facilities.

Objective

The objective of this work was to conduct laboratory investigations in support of developing accelerated aging tests that can track the degradation of various roofing membrane materials.

Approach

Physical and mechanical property tests were performed on both new and aged membrane material samples. The research was designed to approximate the process described in *Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials* (ASTM E 632-82). The initial phases of the study centered on (1) characterizing roofing membranes and performance characteristics, (2) identifying degradation factors and mechanisms, and (3) investigating test methods for use in tracking the degradation and performance of these materials. The artificial aging tests investigated in this phase will be correlated with in-service exposure using property test data from the artificially aged materials and field-exposed samples to develop performance models and predictive service life tests.

Mode of Technology Transfer

This research will provide a basis for establishing standard tests and criteria for determining a roofing material's ability to perform both at the time of application

and after several years of exposure. It is recommended that these tests and criteria be incorporated into the appropriate UFGS for roofing. It is also recommended that the final results of this study be submitted to ASTM for consideration in the development or revision of ASTM roofing material standards.

Units of Weight and Measure

U.S. standard units of measure are used throughout this report. A table of conversion factors for Standard International (SI) units is provided below.

SI conversion factors		
1 in.	=	2.54 cm
1 ft	=	0.305 m
1 sq in.	=	6.452 cm^2
1 sq ft	=	0.093 m^2
1 gal	=	3.78 L
1 lb	=	0.453 kg
1 psi	=	6.89 kPa
°F	=	(°C x 1.8) + 32

2 Previous Research

Earlier work by CERL has addressed (1) characterization of roofing membrane materials, (2) performance, and (3) predictive service life tests. Follow-up laboratory investigations also were conducted to standardize test methods and degradation-tracking techniques. Summaries of those studies are presented below.

Development of Predictive Service Life Tests

A previous CERL study (1) characterized roofing membrane materials based on in-service performance requirements and criteria; (2) identified critical performance characteristics and properties; and (3) identified degradation factors and mechanisms that may be incorporated into the development of accelerated aging service life tests. That work is documented in CERL Interim Report FM-94/03, *Predictive Service Life Tests for Roofing Membranes: Phase 1*.

The membrane materials selected for the study were asphalt built-up roofing (BUR), poly [vinyl choloride] (PVC,) styrene-butadiene-styrene (SBS) modified bitumen (MB), atactic polypropylene (APP) MB, and ethylene propylene diene terpolymer (EPDM). These generic roofing material types comprise the large majority of membranes used on Army projects today.

Performance Characteristics and Criteria

The Phase 1 study found that many existing and proposed performance criteria for roofing membranes are based on changes measured in material properties between new and artificially aged membrane specimens. However, these performance criteria have not been verified by field experience, outdoor weathering, or life-cycle tests.

Physical property tests are useful in evaluating the characteristics of a single generic membrane type (e.g., comparing one PVC membrane to another). However, they should be only of secondary interest when comparing different membrane types because (1) different materials have different degradation mechanisms and (2) the standard tests for each generic membrane material are exclusive to that material and not transferable to other materials.

Some observers mistakenly believe that any membrane will fail when it falls below a minimum value for a physical property (such as tensile strength, elongation, etc.), and similarly believe that the membrane will endure as long as it maintains those minimum values. In reality, concepts such as these are oversimplified and do not correlate reliably with the very complex nature of weathering effects.

Degradation Factors and Mechanisms

Degradation factors are defined as external conditions that adversely affect the performance of building materials and components. Major factors affecting the performance life of roofing membranes include temperature, solar radiation, precipitation, and ozone.

Temperature is the relative measure that indicates the capacity of a body to transfer heat. For roof surfaces, the temperature largely depends on the quantity of solar radiation, the degree of cloud cover, and the absorbance of solar radiation due to roof color. The thermal history of a roofing membrane is the single greatest factor affecting the durability of the roofing system. Leikina et al. (1971) showed that thermal history was a greater influence on polymer tensile strength and elongation than radiation exposure, duration of wetness, or total test time.

Solar radiation refers to the entire electromagnetic spectrum that radiates from the sun. To the roofing industry, the ultraviolet (UV) spectrum is of greatest interest in terms of membrane degradation. Organic fibers and fabrics are particularly sensitive to UV radiation, losing tensile strength, elongation, and energy to break. Plastics of all kinds are also highly vulnerable because UV radiation readily breaks chemical bonds within the polymers.

Precipitation takes many forms in temperate climates, including fog, rain, snow, ice, and hail. However, it is the duration of wetness rather than the quantity of precipitation that plays the greatest role in membrane deterioration. Assuming that adequate design and construction minimize the amount of ponded water on a membrane, the majority of the 'wet time' is a result of condensation rather than actual precipitation. Hail is potentially a very damaging form of precipitation that applies such acute mechanical stress that it can puncture some membrane materials.

Ozone occurs naturally in the atmosphere, but concentrations can be radically increased by pollution arising from human activities. Organic pollutants in the atmosphere quickly oxidize when exposed to sunlight, resulting in synthesized ozone. The concentration of ozone in polluted air can be 10 times greater than the levels

found in natural clean air. Ozone is very reactive with many membrane materials, and causes deterioration of all polymers with double bonds that are under stress.

All of these factors cause sequences of changes that are defined as degradation mechanisms (ASTM E 632), and these mechanisms cause detrimental changes in the properties of the various roofing materials. The most commonly tracked physical changes caused by weathering include a loss of strength, reduction in elongation to failure, and increased water content. Membrane materials also are subject to complex chemical reactions and morphological changes.

Accelerated Aging Tests

In accelerated aging tests, the degradation mechanisms of materials are intentionally accelerated to greatly exceed the degradation rates expected in service. The different stresses typically used to accelerate the aging process include heat (aging at 60 – 150 °C), ultraviolet radiation (aging in a UV light chamber), water (spray or soak), and mechanical load.

Heat exposure is the most common accelerated aging method. Every accelerated aging method includes heat as one of the applied degradation factors, and heat aging is the method of choice for bitumens, modified bitumens, EPDM, and PVC. Most heat-driven aging tests for building materials use a temperature of 70 °C.

Ultraviolet radiation exposure in the laboratory is provided by sunlight carbon arcs (ASTM G 23), xenon arcs (ASTM G 26) UV fluorescent, or mercury lamps (ASTM G 53). The solar radiation that reaches the surface of the earth is cut off by the atmosphere at about 300 nm. This is important because samples exposed to wavelengths lower than this threshold are likely to exhibit different reactions than observed in natural weathering. Therefore, proper selection of light sources is important in order to achieve valid results for accelerated weathering tests.

Water exposure is part of many accelerated testing programs. Water spray is used in some programs to provide a thermal shock to the samples and to wash away any water-soluble degradation products. Other test programs use condensing humidity as a water exposure mode.

Some testing procedures measure the time needed for an applied load to dissipate, and some regard the relaxation time at various temperatures to be an index of durability. Dead loads are often used in service life tests to evaluate for creep-to-failure.

Service Life Prediction

Predictive service life tests involve both property measurement tests and accelerated aging tests. They are designed to predict the service life or to compare the relative durability of materials over a duration much shorter than the expected service life. Statistical techniques are commonly used to estimate the mean exposure time to failure within a specific reliability. Both Nelson (1990) and Martin (1982) provide the mathematics for service life reliability tests.

Ideally, to perform comparative service life reliability tests it is necessary to (1) define failure, (2) have physical and chemical test methods to track the rate of degradation, and (3) expose representative samples of each material to identical stresses.

Investigations by the authors and others (Mathey and Cullen 1974; Mathey and Rossiter, June 1977; Strong 1983) indicate that energy-to-break is the most promising candidate for a physical property that may serve to track roofing membrane degradation. Energy-to-break is calculated as the area under the load-strain curve to break or to first peak. However, different ASTM test methods are used for measuring the tensile properties of each major membrane type (i.e., BUR, PVC, MB, EPDM). If energy-to-break is to be used for tracking membrane performance and comparing different membranes, then a universal test method for tensile testing is needed.

In developing service life prediction tests, it is also highly desirable to identify a single factor that can be measured to trace the rate of chemical degradation for all the materials. The carbonyl group of organic compounds showed significant potential as such a factor. The various roofing materials are all chemically complex, and each is very different from the others. However, being composed largely of organic molecules, they all form free radicals during the weathering process. This phenomenon could lead to formation of compounds that contain carbonyl groups (those having C=O bonds). These groups have an infrared absorbance at about 1710 – 1720 cm^{-1}, which can be measured.

The change in carbonyl concentration has previously been used successfully to track the deterioration of asphalt (Greenfield and Weeks, October 1963), PVC (Matsumoto, Ohshima, and Hasuda 1984) and a long list of other polymers (Winslow, Matreyek, and Trozzolo 1972). This concept has been used to measure the difference in weathering rate for liquid-applied neoprene, chlorosulphated polyethylene (CSPE or Hypalon®), and polyvinylfluoride (Tedlar®).

To validate the measurements made during the accelerated aging tests and to measure the effect (if any) of the different climates, representative samples should be randomly chosen for the various outdoor exposures. A requirement for making reliable comparisons between materials is that researchers must expose all accelerated aging samples to identical sets of exposure stress. At least part of the stress applied to accelerate the aging of samples must include heat because temperature is so important in influencing the durability of materials.

Recommendations From the Study

The Phase I study produced the following recommendations:

- Develop a single standardized load-strain test method that can be used to determine energy-to-break at low temperatures for the different roofing membrane materials. The test should meet the necessary requirements of an ASTM standard test method.
- Conduct laboratory investigations to determine the validity of using energy-to-break and carbonyl concentration for tracking physical and chemical degradation of the different roofing membrane materials. This should be accomplished by exposing material samples to accelerated aging tests of incremental durations to determine the correlation of both properties with time of exposure.
- Conduct long-term in-service tests on samples in different climates.
- Conduct accelerated aging tests on samples using different combinations of aging stresses.
- Develop degradation models for predicting service life and comparing relative durabilities of roofing membrane materials.

Laboratory Investigations of Standardized Test Methods and Degradation-Tracking Techniques

Based on the recommendations from Phase I, researchers conducted laboratory investigations that were considered necessary before initiating accelerated aging and in-service tests. A single, standardized load-strain test method was developed to determine energy-to-break for the different roofing materials. The new method uses one test temperature, jaw-separation rate, sample size, and sample configuration for all membrane materials. In addition, laboratory experiments were conducted to test the validity of using energy-to-break and carbonyl concentration to track physical and chemical degradation of the different roofing membrane materials. The details of these studies, published previously (Cash 1996), are summarized below.

Load-Strain Test Harmonization

A preliminary test program was conducted using five different roofing membranes to develop a standardized test method for determining energy-to-break. The task was to select the load-strain test parameters that will minimize the reproducibility range while still being consistent with the character of the membranes under study.

Five specimens each of the five membranes were tested at each combination of three jaw-separation rates and three test temperatures (for a total of 225 specimens). These data were used to calculate the mean for maximum load, strain at maximum load, and energy to maximum load for each of the five membrane types. Then the coefficient of variation for each set of data for each membrane was calculated. Based on the results of these tests, a jaw-separation rate of 0.85 mm/sec was chosen for use in all subsequent testing. None of the test temperatures (-18 °C, 0 °C, and 23 °C) showed significant advantage over the others.

Validation of Test Methods for Tracking Degradation

Additional laboratory studies were conducted to determine the validity of the energy-to-break and carbonyl index tests for tracking physical and chemical degradation of different roofing materials. This was accomplished by exposing samples of various materials to heat aging for different incremental time durations to determine the correlation of both properties with time of exposure.

Samples from 14 different membranes were selected for the study to maximize the variability between samples. They included three EPDM products, three PVC products, three two-ply SBS MB systems, three two-ply APP MB systems, an asphalt / four-ply glass fiber felt BUR system, and an asphalt / four-ply organic felt BUR system.

Sample sets of the membrane materials were aged at three different constant temperatures: 23 °C, 40 °C, and 80 °C. The samples at 23 °C track the changes due to simple room temperature aging. It was decided not to go higher than 80 °C in order to avoid possible changes in the degradation processes that occur at higher temperatures.

Tensile testing was performed on unexposed samples and individual sets after reaching exposure times of 672 hours (28 days), 2000 hours (83 days), and 3000 hours (125 days). Based on analyses of the data, the test method proved useful in comparing the load-strain fundamental properties of the membranes. These results, along with previous work by others (Mathey and Cullen 1974; Mathey and

Rossiter, June 1977; Strong 1983) indicate that the energy-to-break parameter seems to be the outstanding physical property candidate for tracking the weathering process. Using a test temperature of 23 °C would allow the procedure to be used for evaluating all materials without the need for testing in an environmental chamber.

Fourier transform infrared (FTIR) spectroscopy analysis was used to investigate the carbonyl index and changes due to heat aging. The absorbance at 1695 to 1715 cm^{-1} was measured to determine the amount of carbonyl groups present. The C-H absorbance in the same sample at 2900 cm^{-1} was measured to determine the quantity of the sample present. The ratio of these absorbencies is an index of the carbonyl concentration.

This study validated the carbonyl index method for bituminous membranes (BUR and modified bitumen). The results were not as promising for the non-bituminous membranes, however. The inherent limitations – due to a high absorption of the carbon black in the EPDM and a big C=O peak caused by the plasticizers in the PVC – prevented using the carbonyl index method for these materials.

Applicability of Modern Analytical Techniques for Detecting Changes

The National Institute of Standards and Technology (NIST) conducted tests on the heat-exposed materials from the validation tests using six different analytical techniques (Rossiter 1995). Along with FTIR spectroscopy, which was used in the carbonyl index investigation, analyses using thermogravimetry (TG), differential scanning calorimetry (DSC), secondary ion mass spectroscopy (SIMS), and nuclear magnetic resonance (NMR) spectroscopy were performed. These techniques were selected because they have been used successfully in characterizing organic materials and changes that occur during exposure to a variety of environments, including heat.

The study demonstrated that the SIMS method could be applied to synthetic membrane materials such as EPDM and PVC, although the interpretation of the method's findings may be difficult due to a lack of experience in applying the method to these materials. Additionally, the NMR method was determined to be applicable to both synthetic and bituminous membrane materials, but the analysis can be time-consuming and impractical for routine use. In general, results of the analyses using the five techniques found no major differences between comparable pairs of the controls and heat-exposed (3000 hrs, 80 °C) samples.

Recommendations From Laboratory Investigations

The findings of these studies prompted the following recommendations:

- Develop a new aging method, perhaps including heat, moisture, UV, and mechanical load, to provide more effective accelerated aging for roofing membrane samples.
- Place new sample sets out in natural exposure at a minimum of three locations for the purpose of verifying accelerated aging test methods.
- Test the new sample sets by different accelerated techniques that include different combinations of stress.
- Perform statistical service-life testing for samples under the most severe accelerated conditions.

3 Accelerated Aging Tests and Service Life Predictions

This chapter reports on the results of material properties testing of 12 membranes used on low-sloped roofs. These materials were tested in unaged condition, after 28 days of exposure in a 70 °C forced-draft oven, and after 60 days of exposure in a QUV* accelerated weathering tester. Testing of the unaged samples measured tensile strength, elongation, cyclical fatigue, water absorption, glass transition temperature, thermal expansion coefficient, puncture resistance, and infrared spectrophotometer traces. Many of these tests were repeated on samples after accelerated aging to measure any significant changes in the respective physical properties.

Materials and Sample Preparation

The 12 roofing membranes shown in Table 1 were selected for testing. All of these products have a substantial history of outdoor performance according to each of their respective manufacturers. The multi-ply bituminous membrane samples, which include the BUR and MB materials (C, D, E, F, G, H), were constructed according to manufacturers instructions.

Nine additional sets of samples were placed on 61 x 76 cm plywood substrates. Three sets were placed on outdoor exposure tables (Figure 1) at each of three different sites (located in central Illinois, central Arizona, and southern Florida). These samples were used to determine changes in properties due to actual weathering and to allow for correlating with the accelerated aging test specimens.

* Manufactured by Q-Panel Lab Products, Cleveland, OH 44145.

Test Methods

Table 2 shows the methods and conditions selected for testing the unaged specimens. The methods selected provide key data relevant to tracking (and therefore predicting) performance. Each membrane was carefully tested using uniform test conditions and standard methods to ensure that the data can be compared across the broad spectra of values that can be expected from testing this variety of materials (from thermoplastic to rubbery) having varying degrees of reinforcement.

Characterization of Unexposed Membrane Samples

The load-strain tests, cyclical fatigue resistance, static puncture resistance, and dynamic puncture resistance were performed on the unaged samples at three different temperatures: -18 °C, 23 °C, and 70 °C. For comparison purposes, the researchers developed a rating system that for each test and test temperature assigns a rating of 100 to the sample having the most desirable property value. For tests such as maximum load to break, 100 would indicate the highest value; for tests such as percent water absorption, 100 would indicate the lowest value. A rating of 0 was assigned to the sample having the least desirable property value, and the ratings for all other samples for a specific test were defined linearly based on the proportional value between 0 and 100.

Load-Strain Properties

Pull tests were conducted on samples using a tensile testing machine as shown in Figure 2. All of these tests used an initial jaw-separation gap of 100 mm and a jaw-separation rate of 0.85 mm/sec. These samples generated three types of load-strain curves. A relatively straight line was generated by each EPDM rubber sample (Figure 3). The TPO samples each generated a sharp peak when the reinforcement ruptured followed by a long tail until the sample ruptured (Figure 4). All of the other samples ruptured at the peak load (Figure 5).

The mean breaking or first peak load of five specimens at each of the three test temperatures is shown in Table 3. Current conventional wisdom suggests that all effective roof membranes have a minimum load at break of 35 kN/m (Mathey 1974) at -18 °C. Except for the EPDM rubber membranes and Sample H, all samples tested comply with this suggested requirement. Sample H is an APP MB, but any hasty conclusion about its lower load at break is given pause by the load at break shown by Sample G – also an APP MB – which is greater than for any other sample. EPDMs, which typically have lower breaking strengths by comparison, accommo-

date load by stretching, as noted by the large elongation values for samples J and K (Table 4).

The ratings in Table 5 show that Sample G had the highest recorded load – 61.9 kN/m for the -18 °C test temperature – and was assigned a rating of 100. Samples J and K had the lowest recorded values – 11.4 kN/m – and were given a rating of 0. Sample F had recorded load of 45.3 kN/m – 68% of the difference between the two extremes – and was assigned a rating of 68. The individual ratings for each test temperature were averaged to calculate the average rating for each membrane.

The loads at first peak or break at the various test temperatures can also provide a measure of thermal susceptibility for each membrane. These data may provide a clue about how membranes might perform in different environments. Sample B, for example, which has its highest rating at 70 °C, indicating that it may perform best in warm environments; Sample G may perform best in cold environments; and Samples B, D, F, and M may perform best in climates with moderate temperatures.

Based on tensile strength alone, Sample B has the highest overall rating (88) of the 12 membranes. However, for resistance of tensile loads, both elongation and energy to break must be considered. Table 5 lists the average elongation at first peak or failure of these samples.

Interestingly, the elongation at break or first peak remains about the same as the testing temperature increases for B (PVC alloy), G (APP MB), L (PVC) and M (PVC) membranes; it decreases for A (TPO); it peaks upward at the 23 °C temperature for F (SBS MB), H (APP MB), J (EPDM), and K (EPDM) membranes; it peaks downward for C (BUR) and D (BUR), and increases for the E (SBS MB) membrane. In addition to elongation, the energy to break or first peak may provide a clue to durability; it is represented by the area under the load-strain curve. Table 6 lists the mean energy to break or to first peak for all three test temperatures.

To provide a basis for comparison of all three tensile properties, ratings were assigned for strain and energy to break, similar to what was done for load. These rating were then averaged for each temperature (see Table 7).

The composite values for:

- A (TPO) and C (BUR) decline significantly with increasing test temperature
- E (SBS MB), F (SBS MB), and G (APP MB) do not drop significantly from -18 °C to 23 °C test temperature, but the latter two drop significantly at the high test temperature

- the PVC and EPDM samples remain relatively constant as the testing temperature increases. The EPDM samples consistently have the highest ratings.

Cyclic Fatigue Resistance

Fatigue resistance of duplicate samples of each membrane was tested at the same three temperatures used for the tensile testing. Researchers cycled the samples at 0.005 mm/s to a 1 mm gap and back for 500 cycles. All of the specimens passed 500 cycles at room temperature. However, a few of the samples – including the two PVC (L and M) – failed when tested at the low temperature. The two EPDM samples (J and K) and sample B (PVC alloy) exhibited bond failures at the elevated temperature (Table 8). Solvent extractions show the crack in Sample C did not extend through the bottom felt ply.

Water Absorption

Water absorption of the samples was measured using the following steps:

1. chamfering the four edges of 4 in. square specimens in triplicate
2. conditioning the specimens at 50 °C for 24 hours
3. weighing the conditioned specimens
4. soaking the specimens in distilled water at 60 °C for 7 days
5. blotting the water off the surface and weighing each specimen
6. calculating the water absorbed as a percentage of the conditioned mass of each specimen
7. observing the condition of each specimen after re-drying or reconditioning for 24 hours in an oven at 50 °C.

The averages of the percent water absorbed are shown in Table 9. All of the water absorption values were at around 3% or lower except for the TPO and PVC alloy, which were at 6.3 and 11.0%, respectively. The higher values for these two samples were likely due to wicking of water within their reinforcing fabrics. (It was noted with interest that none of the specimens showed any blistering or other distress after reconditioning).

Thermal Properties

The National Research Council, Institute for Research in Construction (Canada) measured the glass transition temperatures and estimated thermal expansion coefficients using differential scanning calorimetry (DSC) and differential thermome-

chanical analyses (TMA) (see Table 9). The estimated thermal expansion coefficient for Sample A is the mean for -20 to 40 °C because the expansion was nonlinear above 40 °C. For Samples C, D, E, and F the thermal expansion coefficient is the mean for the -20 to 60 °C range. Thermal expansion was relatively linear for the other samples, and the -20 to -90 °C range was used to estimate the coefficient. The coefficients for bituminous BUR and MB samples (C,D, E, F, G, H) were in the 20 x 10^{-5} / °C range or greater, and the remaining single-ply membrane samples were in the 10 x 10^{-5} / °C range.

Static Puncture Resistance

The static puncture resistance of the unaged samples was measured at the three test temperatures. The data and ratings for the unexposed samples are shown in Table 10. Except for samples F and H, the BUR and MB membranes passed at the 250 N load at -18 °C but failed at considerably lower loads when tested at 23 °C, and at even lower loads at 70 °C. The remaining samples passed the 250 N load at all test temperatures. As was done for the tensile properties, the individual sample ratings for each test temperature were averaged to calculate a mean rating for all temperatures.

Dynamic Puncture Resistance

Table 11 lists the dynamic puncture resistance of the unexposed membranes. As seen by examining the mean ratings for all three test temperatures, the MB samples had the highest overall ratings and the EPDM samples had the lowest.

Overall Unexposed Ratings

Ratings of all the tests performed on the unexposed membranes are summarized in Table 12. The rightmost column provides a mean rating that assumes equal weighting of each of the 21 different test/temperature combinations. The EPDM membranes, as a group, have the highest mean ratings (67). However, they also have the lowest dynamic puncture resistance and tensile strength.

Infrared Spectrophotometer Analyses

Infrared scans of the samples were conducted both before and after heat aging (see Appendix), and these data have been normalized to reveal the changes due to heat aging. The researchers were unable to devise a meaningful rating system for such a test. However, the scans do illustrate the changes that take place in these membranes due to heat aging.

Change Ratings

In order to assess and compare material changes after submitting membrane materials to accelerated aging procedures, a change rating method was established. The change ratings for each test property are based on the absolute percentage of change due to artificial aging as compared to the sample having the highest percent of change for that property. As an example: for a given property, 148% was the highest absolute change. That particular sample is assigned a change rating of "0". Samples experiencing no significant change are assigned a change rating of "100". A sample that changes 61% is given a change rating of 59 $(100 - \frac{61}{148}(100))$.

The change ratings are intended to provide a quantitative means of measuring the amount of change that materials undergo, but they do not attempt to consider whether the change may represent an improvement in a particular property. While it is feasible that some specific property, such as energy to break, may improve with time or environmental exposure, it does not follow that all other material properties affecting performance would likewise improve. In fact, it may be considered axiomatic that materials tend to degrade (rather than improve) as a result of age, heat, mechanical stress, and so on. Therefore, the change rating method used here puts emphasis on the idea that chemical and physical changes caused by service exposure are, overall, a reliable indicator that the material is no longer new, but is degrading.

Changes Due to Heat Aging

Samples of each of the 12 materials were tested again after exposure to 70 °C temperature for 28 days. For those property tests that provided sufficient data, the researchers calculated the statistical significance of the changes in each of the properties due to heat aging using the *student's t* distribution and a significance level of 0.05%. Those changes that were found to be significant are reported in the tables. A value of "NC" means that no significant change was recorded for that property.

Tensile Properties

The tensile properties of the various membranes were measured at room temperature after being heat-aged at 70 °C for 28 days. Property values, percent changes, and change ratings for the tensile properties are shown in Table 13. Heat aging increased the maximum load for Samples A (TPO) and C (BUR). The change in maxi-

mum load due to heat aging is insignificant in samples B, D, E, F, H, J, and L. Heat aging decreased the maximum load in Samples G (APP MB), K (EPDM), and M (PVC).

Increases in strain-to-first-peak due to heat aging were found in Samples A, C, and F. The changes in strain-to-first-peak were not significant in Samples B, D, J, K, and M. Significant decreases in the strain were observed in Samples E (SBS MB), H (APP MB), and L (PVC). The energy-to-maximum-load due to heat aging increased by 79% for Sample A, increased by 257% for the BUR sample C, and decreased moderately for the modified bitumen samples (E, F, G, and H). The energy-to-maximum-load did not change significantly in the PVC and EPDM samples.

Water Absorption and Glass Transition Temperature

The changes in water absorption and glass transition temperature are shown in Table 14. Most of the samples did not exhibit significant change in water absorption after heat aging compared to the unaged samples. Samples H (APP MB) and L (PVC) showed increases of 39% and 21%, respectively.

The changes in glass transition temperatures were modest and mixed. Most of the samples experienced insignificant change. The glass transition temperature for Sample C (BUR) increased by 5% and decreased for samples E (SBS MB), G (APP MB), and L (PVC).

Thermal Expansion Coefficient and Cyclic Fatigue

Changes in the thermal expansion coefficient due to heat aging were not statically significant at the 0.05% level. All of the heat-aged samples passed 500 cycles of the cyclic fatigue test conducted at room temperature.

Static Puncture Resistance at 70 °C

The membrane samples tested for static puncture resistance after heat aging gave results identical to those for the samples tested before heat aging.

Dynamic Puncture Resistance at -18 °C

The changes in dynamic puncture resistance due to heat aging are shown in Table 15. These data show that heat aging increased the dynamic impact resistance of Samples A, L, and M (the TPO and PVC samples). Heat aging decreased the puncture resistance of three of the MB samples (F, G, H) and one of the EPDM samples (K). The puncture resistance of the other membranes was unchanged.

Rating the Changes Due to Heat Aging

For test/temperature combinations used for the heat-aged samples, Table 16 gives the change ratings due to heat aging. A mean value of the change ratings for the nine tests for each sample is provided. The mean change rating for Sample C (BUR) was lowest at 59; the remaining samples had a mean change rating of 76 or higher.

Infrared Analyses

The Appendix to this report shows plots of before and after heat-aging scans harmonized to the carbon-hydrogen (C-H) concentration for each of the membranes studied. In each display, the solid line represents the curve before heat aging and the dashed line represents the curve after heat aging. Chemical changes are generally visible in the center of the plot, and physical changes, such as the degree of crystallinity, are shown to the right side of the spectra. Based on the plots in the Appendix, the following observations were made for each of the 12 materials.

Sample A (TPO). The bottom surface shows no significant chemical changes and an increase in crystallinity. The top surface shows an increase in amino or amide groups and the loss of unidentified groups represented by peaks near 750, 1000, 1250, and 1400 cm^{-1}.

Sample B (PVC alloy). The changes do not appear to be significant. There may be a slight increase in ammonia and ring structures.

Samples C (BUR) and D (BUR). No significant changes were observed. There may be a slight increase in the -C=O (carbonyl groups).

Sample E (SBS MB). These scans show little change due to heat aging. There was a slight loss in -C=O groups and a slight loss in what may be sulfur groups.

Sample F (SBS MB). These scans show a loss in -OH groups (possibly) and unidentified groups near 1600 and 1000 cm^{-1}.

Sample G (APP MB). These scans show an increase in -OH (possibly water) and the loss of unidentified peaks near 1000 cm^{-1}.

Sample H (APP MB). An increase was observed in -C=O groups and in unidentified groups near 1000, 1100, and 1300 cm^{-1}.

Samples J (EPDM) and K (EPDM). These scans are very similar. The after-heat-aging scan shows an increase in amine (NH) groups in Sample J and a decrease across a broad area from 1000 to 3000 cm^{-1} in both samples, probably due to the loss of processing oils.

Samples L (PVC) and M (PVC). These scans show little change due to heat aging.

Changes Due to UV Aging

Pristine samples of 11 of the 12 materials were tested again after exposure to UV-moisture-heat cycles for 62.50 days (1500 hrs) in an accelerated weathering tester. (No results are available for Sample F because all of the SBS MB membrane samples softened, folded, and adhered to themselves during the exposure cycle.) The accelerated weathering cycles consisted of 20 hours of UV exposure under UVA 340 fluorescent lamps at 60 °C, and 2 hours of condensation at 40 °C. Static puncture resistance and infrared analyses of the UV-aged samples were not performed due to limited availability of samples and the limited benefit gained from these particular tests.

The statistical significance of changes and change ratings was determined using the same procedures as for the heat-aged samples.

Tensile Properties

Values, percent changes, and change ratings for tensile properties of the UV-aged specimens are shown in Table 17. Samples A (TPO), D (BUR), and J (EPDM) underwent increases in maximum tensile load when compared to the unaged materials. These samples, along with Sample M (PVC), also exhibited an increase in elongation. Samples G (APP MB), K (EPDM), and M (PVC) underwent decreases in strength. The energy to break decreased for the MB samples and the PVC alloy sample. The BUR and PVC samples exhibited no significant changes in their energy to break values, but Samples A and J increased by 121% and 39%, respectively.

Water Absorption and Glass Transition Temperature

The changes in water absorption and glass transition temperatures after UV aging are shown in Table 18. The two BUR samples (C and D) experienced large decreases in water absorption after UV aging. The absorption values for samples B (PVC alloy) and G (APP MB) increased moderately. None of the samples underwent significant change in glass transition temperature.

Thermal Expansion Coefficient and Cyclic Fatigue

As shown in Table 19, significant decreases in the thermal expansion coefficient after UV aging were exhibited by the PVC alloy and both EPDM samples as well as Sample E (SBS MB) and Sample L (PVC). The changes from the original values were all in the 38 to 53% range. All UV-aged samples passed the cyclic fatigue test, as the unaged samples did.

Dynamic Puncture Resistance at -18 °C

The changes in dynamic puncture resistance due to UV aging are shown in Table 20. All 12 samples showed increases after exposure. Sample G experienced an increase of 44% from its original value in the unaged condition, and the other samples increased by 89% or more.

Rating the Changes Due to UV Aging

Table 21 gives the change ratings due to UV aging. A mean rating for the 11 samples tested is provided in the rightmost column for all of the property tests conducted. (As explained on page 26, the static puncture resistance test was not performed.) In examining the results, Sample A (TPO) and Sample J (EPDM) had the lowest mean change ratings — 51 and 68, respectively. The remainder of the materials had change ratings in the 75 to 86 range.

Combined Ratings of Unexposed Materials and Change Ratings Resulting From Accelerated Aging

Table 22 includes an average of the unaged rating, change rating due to heat aging, and change rating due to UV aging for each of the properties tested. Combined averages are also provided (in bold type) for each of the six different material types (BUR, SBS MB, APP MB, EPDM, PVC, and other thermoplastics). It is interesting to note that the mean averages for the five other generic material types are greater than the mean rating for conventional BUR membranes (i.e., 64), which have for 100 years proven to perform well in service when installed properly.

4 Conclusions

The main purpose of performing these tests was to provide the baseline for developing degradation curves. When in-service exposure data begin to come in, correlation of these results with the accelerated aging data can begin. This correlation will provide the basis for developing performance models and predictive service life tests.

The conclusions presented below pertain only to the accelerated aging test results. They will have to be revisited and possibly modified in light of data produced by the in-service exposure tests that are now under way.

- Considering only the preliminary characterization test data, which include load testing and puncture resistance testing at three temperatures (Table 12), SBS MB Sample F and the two EPDM materials (Samples J and K) had the highest ratings. However, Sample F is the material that failed completely during the UV aging cycles. The two BUR materials (Samples C and D) and the other SBS MB (Sample E) had the lowest ratings in the unaged condition.
- Considering only the changes due to heat aging, Sample D (BUR), the two EPDM samples and Sample M (PVC) had the highest change ratings. The other BUR sample (C) had the lowest rating.
- Considering only the changes due to UV aging, the TPO material and one of the EPDM materials (Sample J) had the lowest mean change ratings when compared to the rest of the materials.
- Combining the unaged rating and the two change ratings, the mean averages for the five other generic material types are greater than the mean change rating for conventional BUR membrane (i.e., 64), which has for 100 years proven to perform well in service when properly specified and installed.

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Figures

Figure 1. Outdoor exposure table with 12 samples at Champaign, IL weathering site.

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Figure 2. Tensile testing of membrane samples.

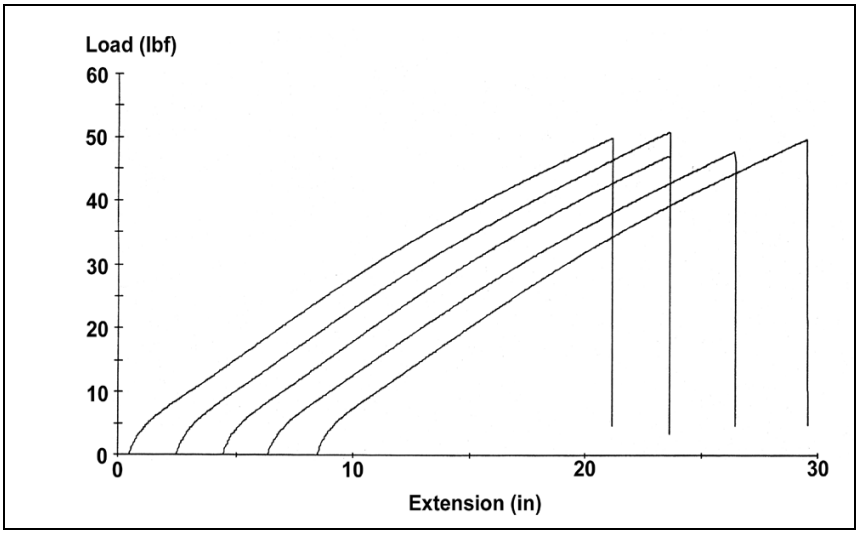


Figure 3. EPDM load-strain curve.

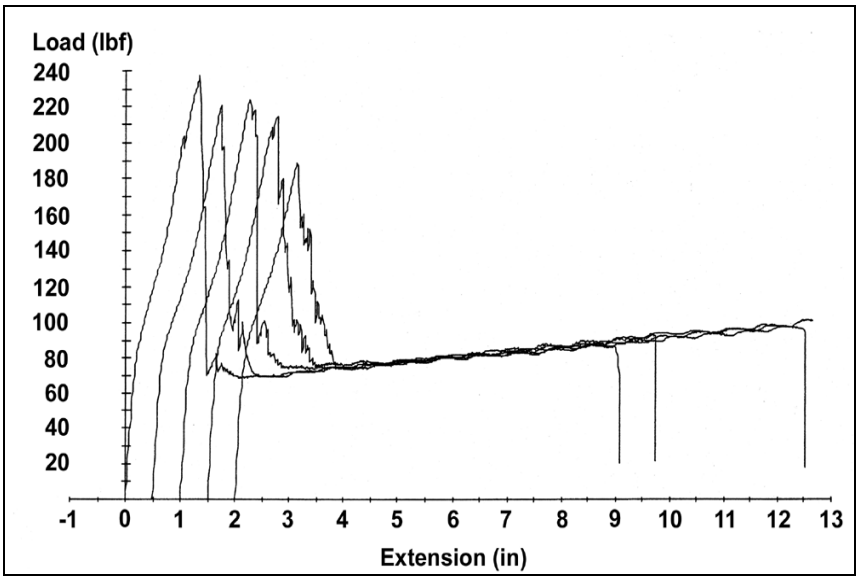


Figure 4. TPO load-strain curve.

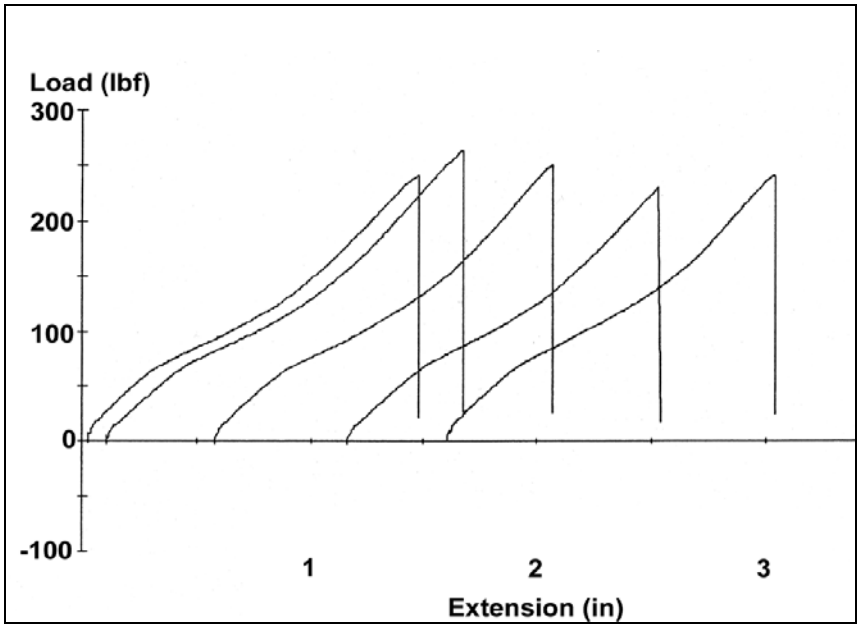


Figure 5. PVC load-strain curve.

Tables

Table 1. Selected roofing membranes.

Code	Membrane	Code	Membrane
A	1 ply TPO – (thermoplastic olefin)	G	2 ply APP modified bitumen
B	1 ply PVC alloy	H	2 ply APP modified bitumen
C	3 ply BUR with glass felts	J	1 ply EPDM, nonreinforced
D	3 ply BUR with glass felts	K	1 ply EPDM, nonreinforced
E	2 ply SBS modified bitumen	L	1 ply PVC, reinforced
F	2 ply SBS modified bitumen	M	1 ply PVC, reinforced

Table 2. General characterization test methods.

Property	Method	Test Conditions
Load-Strain Properties	D2523	strips @ -18°C, 23°C, 70°C
Cyclic Fatigue Resistance	D5849	-18°C, 23°C, 70°C
Water Absorption	D570	one week in water @ 60°C
Glass Transition Temperature	DSC	thermal phase transition temperature
Thermal Expansion Coefficient	TMA	length change as a function of temperature.
Static Puncture Resistance	D5602	-18°C, 23°C, 70°C
Dynamic Puncture Resistance	D5635	-18°C, 23°C, 70°C
Infrared Spectroscopy		

Table 3. Mean breaking or first peak load for unexposed samples.

	-18 °C	23 °C	70 °C
Sample	**kN/m**	**kN/m**	**kN/m**
A (TPO)	37.8	11.4	3.2
B (PVC alloy)	42.9	29.6	23.8
C (BUR)	38.0	16.3	3.5
D (BUR)	38.5	29.6	6.0
E (SBS MB)	39.2	13.8	7.8
F (SBS MB)	45.3	28.5	5.6
G (APP MB)	61.9	28.0	5.1
H (APP MB)	33.8	23.6	7.4
J (EPDM)	11.4+	8.6	4+
K (EPDM)	11.4+	8.8	5+
L (PVC)	37.4	25.2	9.6
M (PVC)	35.9	28.9	17.3

Legend: "+" = elongation greater than environmental chamber.

Table 4. Mean percent elongation at first peak or failure for unexposed samples.

	-18 °C		23 °C		70 °C		Mean Rating
Sample	**%**	**Rating**	**%**	**Rating**	**%**	**Rating**	
A (TPO)	31	9	23	4	5.4	0	4
B (PVC alloy)	37	11	38	6	40	13	10
C (BUR)	6.2	0	4.0	0	7.9	1	0
D (BUR)	6.3	0	4.1	0	7.5	1	0
E (SBS MB)	7.6	1	13	2	14	3	2
F (SBS MB)	8.8	1	70	12	21	6	6
G (APP MB)	8.3	1	11	1	7.7	1	1
H (APP MB)	26	7	89	16	23	6	10
J (EPDM)	278+	100	537	100	282+	100	100
K(EPDM)	265+	95	510	95	282+	100	97
L (PVC)	36	11	39	7	25	7	8
M (PVC)	32	9	33	5	32	10	8

Table 5. Load ratings for unexposed samples.

Sample	-18 °C	23 °C	70 °C	Mean Rating
A (TPO)	53	13	0	22
B (PVC alloy)	63	100	100	88
C (BUR)	53	37	1	30
D (BUR)	54	100	14	56
E (SBS MB)	55	25	22	34
F (SBS MB)	68	95	12	58
G (APP MB)	100	92	9	67
H (APP MB)	45	71	20	45
J (EPDM)	0+	0	4+	1+
K (EPDM)	0+	1	9+	3+
L (PVC)	52	79	31	54
M (PVC)	49	97	68	71

Table 6. Energy to break or to first peak for unexposed samples.

	-18 °C		23 °C		70 °C		Mean Rating
Sample	kN/m	Rating	kN/m	Rating	kN/m	Rating	
A (TPO)	29	31	6.8	5	0.42	0	12
B (PVC alloy)	30	32	20	19	18	56	36
C (BUR)	4.6	0	1.4	0	0.54	0	0
D (BUR)	4.2	0	3.0	2	0.91	2	1
E (SBS MB)	6.5	3	5.1	4	2.6	7	5
F (SBS MB)	85	100	64	63	3.0	8	57
G (APP MB)	10	7	7.7	6	0.98	2	5
H (APP MB)	30	32	60	59	4.7	14	35
J (EPDM)	74+	86	97	97	24+	75	86
K(EPDM)	70+	81	100	100	32+	100	94
L (PVC)	27	28	19	18	4.9	14	20
M (PVC)	22	22	19	18	11	34	25

Table 7. Composite rating for tensile properties for unexposed samples.

Sample	-18 °C	23 °C	70 °C
A (TPO)	31	7	0
B (PVC alloy)	35	42	56
C (BUR)	18	12	1
D (BUR)	18	34	6
E (SBS MB)	20	10	11
F (SBS MB)	56	57	9
G (APP MB)	36	33	4
H (APP MB)	28	49	13
J (EPDM)	62	66	60
K (EPDM)	59	65	70
L (PVC)	30	35	17
M (PVC)	27	40	37

Table 8. Cyclic fatigue – 500 cycles for unexposed samples.

Sample	-18 °C	23 ºC	70 ºC	Type of Failure
A (TPO)	pass	pass	pass	
B (PVC alloy)	fail	pass	pass/fail	buckled & separated over joint
C (BUR)	pass/fail	pass	pass	bottom ply cracked
D (BUR)	pass	pass	pass	
E (SBS MB)	pass	pass	pass	
F (SBS MB)	pass	pass	pass	
G (APP MB)	pass	pass	pass	
H (APP MB)	pass	pass	pass	
J (EPDM)	pass	pass	pass/fail	buckled & separated over joint
K (EPDM)	pass	pass	pass/fail	buckled & separated over joint
L (PVC)	fail	pass	pass	buckled & separated over joint
M (PVC)	fail	pass	pass	buckled & separated over joint

pass/fail = one specimen passes and one fails.

Table 9. Percent water absorption, glass transition temperature, estimated thermal expansion coefficient for unexposed samples.

Sample	Water Absorption		Glass Transition		Thermal Exp. Coef.	
	%	Rating	°C	Rating	X 10^{-5}/°C	Rating
A (TPO)	6.3	48	-36	45	7.5	100
B (PVC alloy)	11.0	0	-44	70	9.6	93
C (BUR)	2.7	86	-21	0	20.4	57
D (BUR)	3.2	80	-21	0	22.2	51
E (SBS MB)	1.8	95	-41	61	37.6	0
F (SBS MB)	1.3	100	-49	85	29.6	27
G (APP MB)	2.5	88	-34	39	36.1	5
H (APP MB)	1.8	95	-30	27	23.1	48
J (EPDM)	2.6	87	-54	100	8.3	97
K (EPDM)	2.9	84	-50	88	10.2	91
L (PVC)	2.9	84	-42	64	8.6	96
M (PVC)	2.2	91	-45	73	10.9	89

Table 10. Static puncture resistance for unexposed samples.

	-18 °C		23 °C		70 °C		Mean Rating
Sample	N	Rating	N	Rating	N	Rating	
A (TPO)	250	100	250	100	250	100	100
B (PVC alloy)	250	100	250	100	250	100	100
C (BUR)	250	100	88	0	67	15	38
D (BUR)	250	100	88	0	57	10	37
E (SBS MB)	250	100	98	6	35	0	35
F (SBS MB)	250	100	250	100	250	100	100
G (APP MB)	250	100	98	6	47	6	37
H (APP MB)	250	100	250	100	250	100	100
J (EPDM)	250	100	250	100	250	100	100
K (EPDM)	250	100	250	100	250	100	100
L (PVC)	250	100	250	100	250	100	100
M (PVC)	250	100	250	100	250	100	100

Table 11. Dynamic puncture resistance for unexposed samples.

	-18 °C		23 °C		70 °C		Mean Rating
Sample	**Joules**	**Rating**	**Joules**	**Rating**	**Joules**	**Rating**	
A (TPO)	3.0	0	5.6	17	8.1	100	39
B (PVC alloy)	5.6	15	5.6	17	5.6	51	28
C (BUR)	5.6	15	5.6	17	5.6	51	28
D (BUR)	8.1	29	5.6	17	3.0	0	15
E (SBS MB)	13.1	57	13.1	67	3.0	0	41
F (SBS MB)	20.6	100	18.1	100	8.1	100	100
G (APP MB)	18.1	86	13.1	67	3.0	0	51
H (APP MB)	15.6	72	13.1	67	5.6	51	63
J (EPDM)	5.6	15	3.0	0	3.0	0	5
K (EPDM)	5.6	15	3.0	0	3.0	0	5
L (PVC)	5.6	15	3.0	0	5.6	51	22
M (PVC)	8.1	29	5.6	17	5.6	51	32

Table 12. Mean ratings for unexposed samples.

Sample	Load -18 °C	Load 23 °C	Load 70 °C	Elongation -18 °C	Elongation 23 °C	Elongation 70 °C	Energy –Break -18 °C	Energy-Break 23 °C	Energy-Break 70 °C	Cyclic Fatigue -18 °C	Cyclic Fatigue 23 °C	Cyclic Fatigue 70 °C	Water Absorption	Glass Trans. Temp.	Expansion. Coefficient	Static Puncture -18 °C	Static Puncture 23 °C	Static Puncture 70 °C	Dyn. Impact -18 °C	Dyn. Puncture 23 °C	Dyn. Puncture 70 °C	Mean
A (TPO)	53	13	0	9	4	0	31	5	0	100	100	100	48	45	100	100	100	100	0	17	100	49
B (PVC alloy)	63	100	100	11	6	13	32	19	56	0	100	50	0	70	93	100	100	100	15	17	51	52
C (BUR)	53	37	1	0	0	1	0	0	0	50	100	100	86	0	57	100	0	15	15	17	51	33
D (BUR)	54	100	14	0	0	1	0	2	2	100	100	100	80	0	51	100	0	10	29	17	0	36
E (SBS MB)	55	25	22	1	2	3	3	4	7	100	100	100	95	61	0	100	6	0	57	67	0	38
F (SBS MB)	68	95	12	1	12	6	100	63	8	100	100	100	100	85	27	100	100	100	100	100	100	70
G (APP MB)	100	92	9	1	1	1	7	6	2	100	100	100	88	39	5	100	6	6	86	67	0	44
H (APP MB)	45	71	20	7	16	6	32	59	14	100	100	100	95	27	48	100	100	100	72	67	51	59
J (EPDM)	0+	0	4+	100	100	100	86	97	75	100	100	50	87	100	97	100	100	100	15	0	0	67
K (EPDM)	0+	1	9+	95	95	100	81	100	100	100	100	50	84	88	91	100	100	100	15	0	0	67
L (PVC)	52	79	31	11	7	7	28	18	14	0	100	100	84	64	96	100	100	100	15	0	51	50
M (PVC)	49	97	68	9	5	10	22	18	34	0	100	100	91	73	89	100	100	100	29	17	51	55

Table 13. Tensile properties at 23 °C after heat aging.

	Max. Load	Strain	Energy - Break	Percent Change			Change Ratings			
Sample	kN/m	%	kN/m	Load	Strain	Energy	L	S	E	Mean
A (TPO)	18.4	28	12.2	61	22	79	60	51	69	60
B (PVC alloy)	NC	NC	NC	NC	NC	NC	100	100	100	100
C (BUR)	40.4	5.8	5.0	148	45	257	0	0	0	0
D (BUR)	NC	NC	NC	NC	NC	NC	100	100	100	100
E (SBS MB)	NC	7.3	2.4	NC	-44	-53	100	2	79	60
F (SBS MB)	NC	88	30.3	NC	26	-53	100	42	79	74
G (APP MB)	22.0	6.3	2.6	-21	-43	-66	88	4	74	55
H (APP MB)	NC	68	47.2	NC	-24	-21	100	47	92	80
J (EPDM)	NC	NC	NC	NC	NC	NC	100	100	100	100
K (EPDM)	7.7	NC	NC	-13	NC	NC	93	100	100	98
L (PVC)	NC	28	NC	NC	-28	NC	100	38	100	79
M (PVC)	23.4	NC	NC	-19	NC	NC	89	100	100	96

Table 14. Water absorption and glass transition temperatures before and after heat aging.

	Water Absorption (%)				Glass Transition Temp (°C)			
Sample	Before	After	% Change	Change Rating	Before	After	Change	Change Rating
A (TPO)	6.3	NC	NC	100	-36	NC	NC	100
B (PVC alloy)	11.0	NC	NC	100	-44	NC	NC	100
C (BUR)	2.7	NC	NC	100	-21	-16	5	29
D (BUR)	3.2	NC	NC	100	-21	NC	NC	100
E (SBS MB)	1.8	NC	NC	100	-41	-48	-7	0
F (SBS MB)	1.3	NC	NC	100	-49	NC	NC	100
G (APP MB)	2.5	NC	NC	100	-34	-38	-4	43
H (APP MB)	1.8	2.5	39	0	-30	NC	NC	100
J (EPDM)	2.6	NC	NC	100	-54	NC	NC	100
K (EPDM)	2.9	NC	NC	100	-50	NC	NC	100
L (PVC)	2.9	3.5	21	46	-42	-44	-2	71
M (PVC)	2.2	NC	NC	100	-45	NC	NC	100

Table 15. Dynamic puncture resistance at -18 °C before and after heat aging.

Sample	Before Joules	After Joules	Change %	Change Rating
A (TPO)	3.0	8.1	170	0
B (PVC alloy)	5.6	5.6	0	100
C (BUR)	5.6	5.6	0	100
D (BUR)	8.1	8.1	0	100
E (SBS MB)	13.1	13.1	0	100
F (SBS MB)	20.6	18.1	-12	93
G (APP MB)	18.1	13.1	-28	84
H (APP MB)	15.6	13.1	-16	91
J (EPDM)	5.6	5.6	0	100
K (EPDM)	5.6	3.0	-46	73
L (PVC)	5.6	8.1	+45	74
M (PVC)	8.1	10.6	+31	82

Table 16. Change ratings of heat-aged samples.

Sample	Load 23 °C	Elongation 23 °C	Energy-Break 23 °C	Cyclic Fatigue 23 °C	Water Absorption	Glass Trans. Temp.	Expansion. Coefficient	Static Puncture 70 °C	Dyn. Puncture -18 °C	Mean
A (TPO)	60	51	69	100	100	100	100	100	0	76
B (PVC alloy)	100	100	100	100	100	100	100	100	100	100
C (BUR)	0	0	0	100	100	29	100	100	100	59
D (BUR)	100	100	100	100	100	100	100	100	100	100
E (SBS MB)	100	2	79	100	100	0	100	100	100	76
F (SBS MB)	100	42	79	100	100	100	100	100	93	90
G (APP MB)	88	4	74	100	100	43	100	100	84	77
H (APP MB)	100	47	92	100	0	100	100	100	91	81
J (EPDM)	100	100	100	100	100	100	100	100	100	100
K (EPDM)	93	100	100	100	100	100	100	100	73	96
L (PVC)	100	38	100	100	46	71	100	100	74	81
M (PVC)	89	100	100	100	100	100	100	100	82	97

Table 17. Tensile properties at 23 °C after UV aging

	Max. Load	Strain	Energy - Break	Percent Change			Change Ratings			
Sample	kN/m	%	kN/m	Load	Strain	Energy	L	S	E	Mean
A (TPO)	20.2	31	15.0	77	35	121	0	0	0	0
B (PVC alloy)	NC	32	16.1	NC	-16	-20	100	54	83	79
C (BUR)	NC	NC	NC	NC	NC	NC	100	100	100	100
D (BUR)	35.6	4.8	NC	20	17	NC	74	51	100	75
E (SBS MB)	NC	NC	1.9	NC	NC	-62	100	100	49	83
F (SBS MB)										
G (APP MB)	17.8	NC	5.5	-36	NC	-29	53	100	76	76
H (APP MB)	NC	58	38.2	NC	-35	-36	100	0	70	57
J (EPDM)	10.8	620	134.4	26	15	39	66	57	68	64
K (EPDM)	8.1	NC	NC	-8	NC	NC	90	100	100	97
L (PVC)	NC	NC	NC	NC	NC	NC	100	100	100	100
M (PVC)	24.7	39	NC	-15	18	NC	81	49	100	77

Table 18. Water absorption and glass transition temperatures before and after UV aging.

	Water Absorption (%)				Glass Transition Temp (°C)			
Sample	Before	After	% Change	Change Rating	Before	After	Change	Change Rating
A (TPO)	6.3	NC	NC	100	-36	NC	NC	100
B (PVC alloy)	11.0	14.4	31	88	-44	NC	NC	100
C (BUR)	2.7	9.5	252	0	-21	NC	NC	100
D (BUR)	3.2	8.3	159	37	-21	NC	NC	100
E (SBS MB)	1.8	NC	NC	100	-41	NC	NC	100
F (SBS MB)	1.3				-49			
G (APP MB)	2.5	3.9	56	78	-34	NC	NC	100
H (APP MB)	1.8	NC	NC	100	-30	NC	NC	100
J (EPDM)	2.6	NC	NC	100	-54	NC	NC	100
K (EPDM)	2.9	NC	NC	100	-50	NC	NC	100
L (PVC)	2.9	NC	NC	100	-42	NC	NC	100
M (PVC)	2.2	NC	NC	100	-45	NC	NC	100

Table 19. Thermal expansion coefficient before and after UV aging.

Sample	Before X 10^{-5}/°C	After X 10^{-5}/°C	Change %	Change Rating
A (TPO)	7.50	NC	NC	100
B (PVC alloy)	9.64	5.3	-45	15
C (BUR)	20.35	NC	NC	100
D (BUR)	22.22	NC	NC	100
E (SBS MB)	37.64	17.6	-53	0
F (SBS MB)	29.65			
G (APP MB)	36.12	NC	NC	100
H (APP MB)	23.1	NC	NC	100
J (EPDM)	8.31	4.0	-52	2
K (EPDM)	10.25	5.2	-49	8
L (PVC)	8.63	5.3	-38	28
M (PVC)	10.86	NC	NC	100

Table 20. Dynamic puncture resistance at -18 °C before and after UV aging.

Sample	Before Joules	After Joules	Change %	Change Rating
A (TPO)	3.0	10.6	253	6
B (PVC alloy)	5.6	10.6	89	67
C (BUR)	5.6	20.6	268	0
D (BUR)	8.1	18.1	123	54
E (SBS MB)	13.1	31.2	138	49
F (SBS MB)	20.6			
G (APP MB)	18.1	26.1	44	84
H (APP MB)	15.6	33.7	116	57
J (EPDM)	5.6	13.1	134	50
K (EPDM)	5.6	10.6	89	67
L (PVC)	5.6	15.6	179	33
M (PVC)	8.1	18.1	123	54

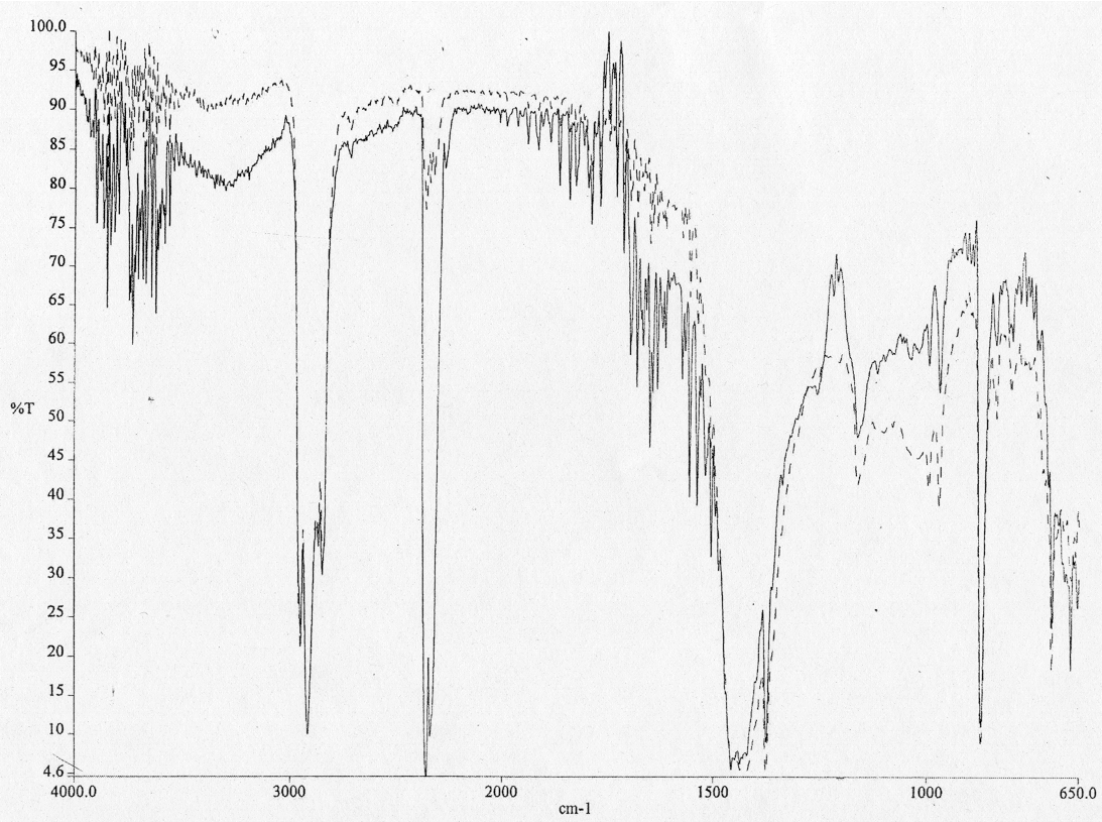
Table 21. Change ratings of UV-aged samples.

Sample	Load 23 °C	Elongation 23 °C	Energy-Break 23 °C	Cyclic Fatigue 23 °C	Water Absorption	Glass Trans. Temp.	Expansion Coefficient	Static Puncture 70 °C	Dyn. Puncture -18 °C	Mean
A (TPO)	0	0	0	100	100	100	100	-	6	51
B (PVC alloy)	100	54	83	100	88	100	15	-	67	76
C (BUR)	100	100	100	100	0	100	100	-	0	75
D (BUR)	74	51	100	100	37	100	100	-	54	77
E (SBS MB)	100	100	49	100	100	100	0	-	49	75
F (SBS MB)										
G (APP MB)	53	100	76	100	78	100	100	-	84	86
H (APP MB)	100	0	70	100	100	100	100	-	57	78
J (EPDM)	66	57	68	100	100	100	2	-	50	68
K (EPDM)	90	100	100	100	100	100	8	-	67	83
L (PVC)	100	100	100	100	100	100	28	-	33	83
M (PVC)	81	49	100	100	100	100	100	-	54	86

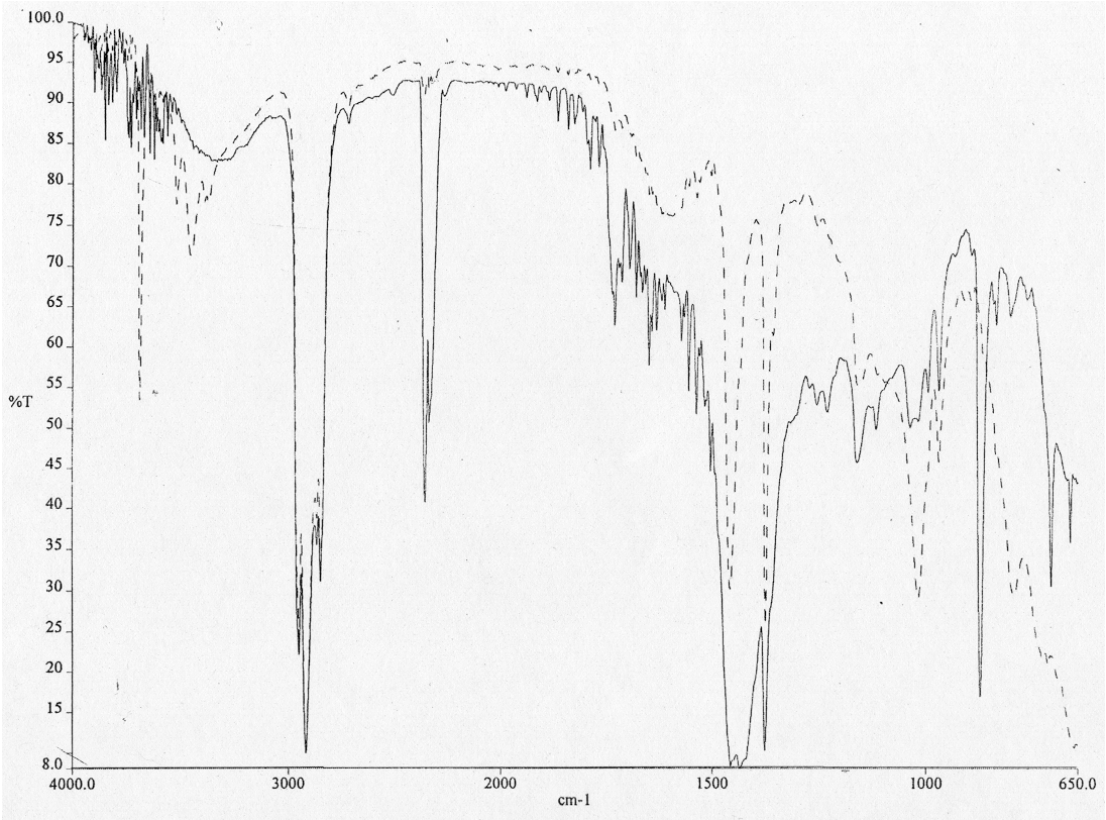
Table 22. Combined ratings of unexposed materials, and change ratings due to accelerated aging.

Sample	Load 23 °C		Elongation 23 °C		Energy Break 23 °C		Cycle Fatigue 23 °C		Water Absorbtion		Glass Trans. Temp.		Expansion Coefficient		Static Puncture 70 °C		Dynamic Puncture –18 °C		Mean	
A (TPO)	24	**62**	18	**36**	25	**46**	100	**100**	83	**73**	82	**86**	100	**85**	100	**100**	2	**31**	59	**69**
B (PVC alloy)	100		53		67		100		63		90		69		100		61		78	
C (BUR)	46	**69**	33	**42**	33	**50**	100	**100**	62	**67**	43	**55**	86	**85**	58	**56**	38	**50**	55	**64**
D (BUR)	91		50		67		100		72		67		84		55		61		72	
E (SBS MB)	75	**86**	35	**26**	44	**58**	100	**100**	98	**99**	54	**73**	33	**48**	50	**75**	69	**83**	62	**72**
F (SBS MB)	98		18		71		100		100		93		64		100		97		82	
G (APP MB)	78	**84**	35	**28**	52	**63**	100	**100**	89	**77**	61	**68**	68	**76**	53	**77**	85	**79**	69	**72**
H (APP MB)	90		21		74		100		65		76		83		100		73		76	
J (EPDM)	55	**58**	86	**92**	88	**94**	100	**100**	96	**95**	100	**98**	66	**66**	100	**100**	55	**53**	83	**84**
K(EPDM)	61		98		100		100		95		96		66		100		52		85	
L (PVC)	93	**91**	48	**50**	73	**73**	100	**100**	77	**87**	78	**85**	75	**86**	100	**100**	41	**48**	76	**80**
M (PVC)	89		51		73		100		97		91		96		100		55		84	

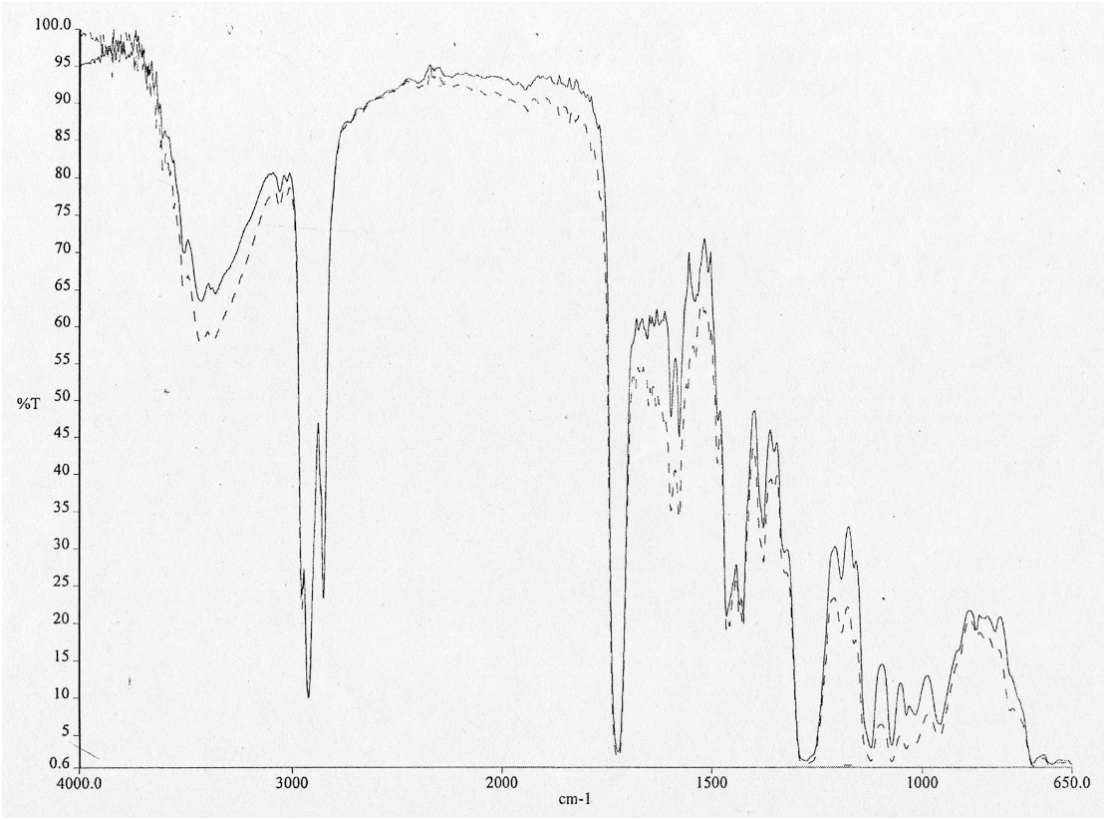
Appendix: Data From Infrared Scans



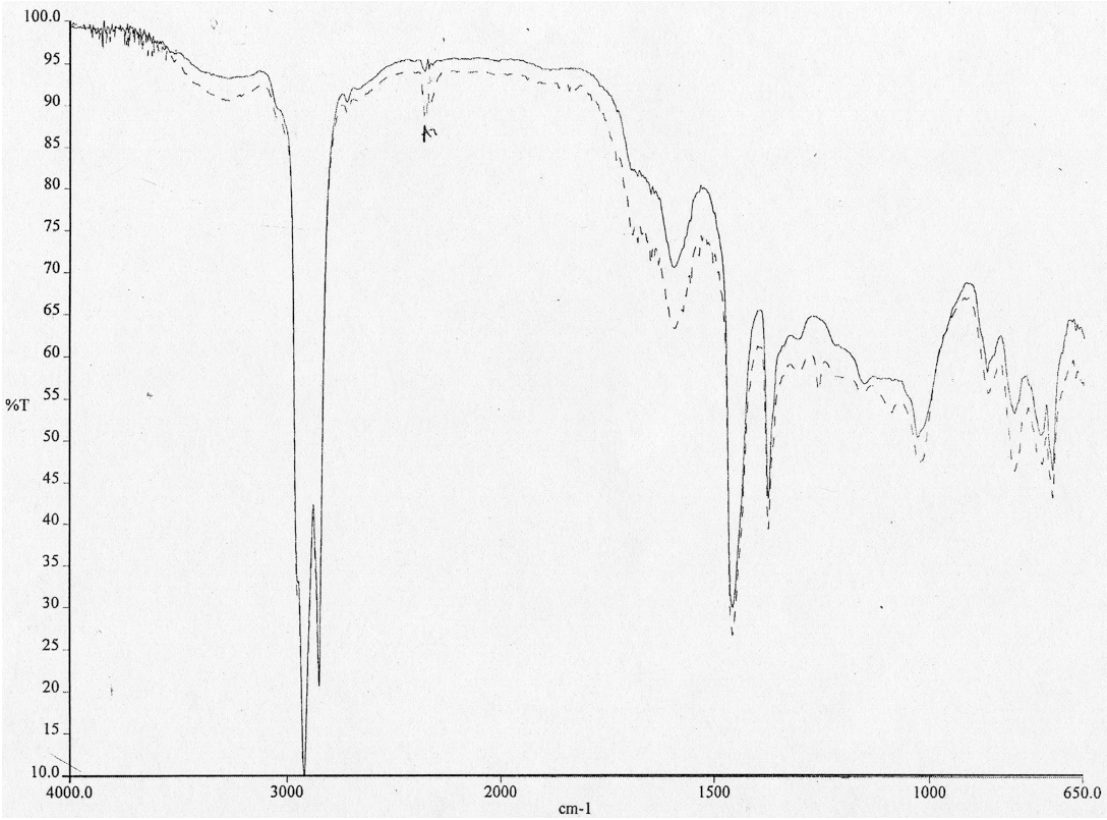
Sample A (TPO), bottom surface.



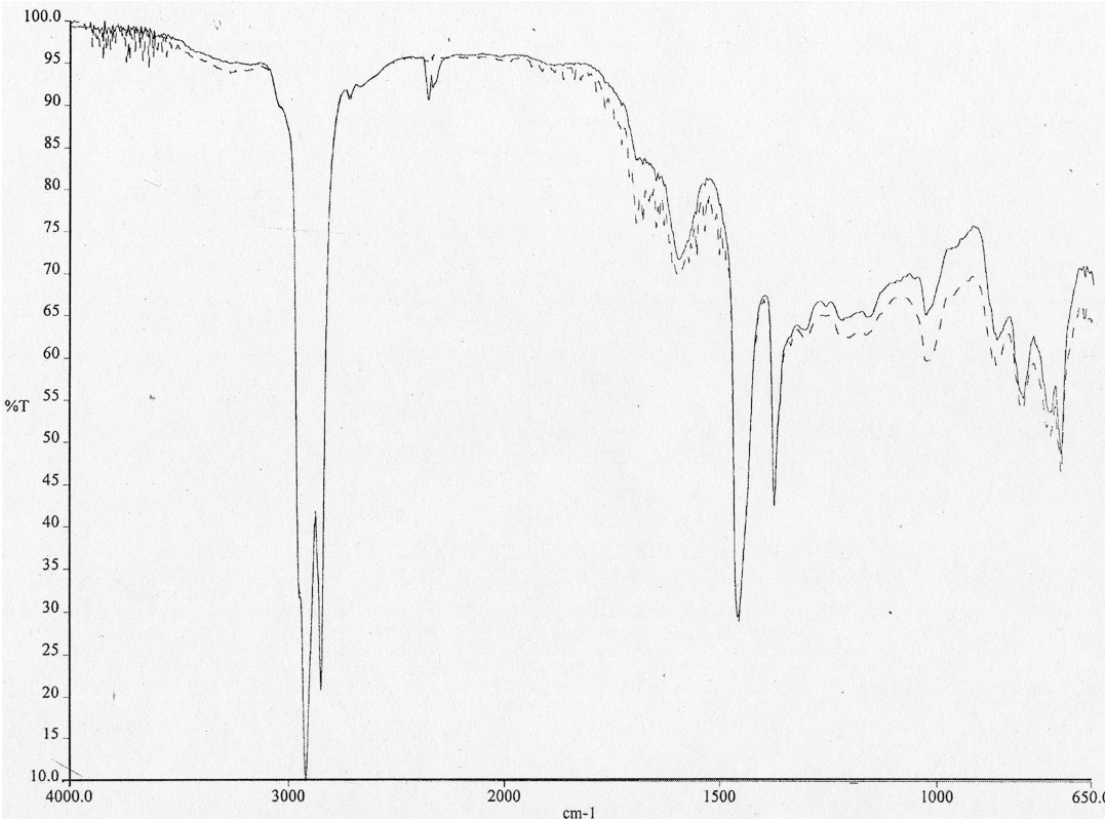
Sample A (TPO), top surface.



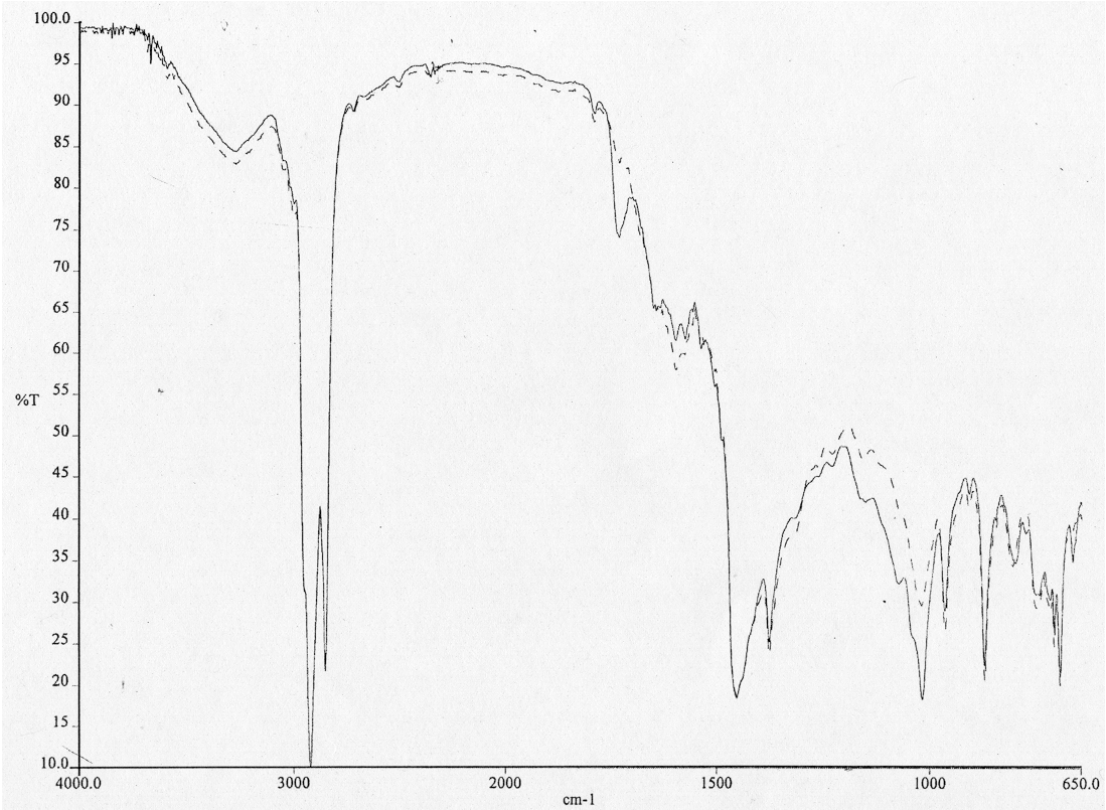
Sample B (PVC alloy), top surface.



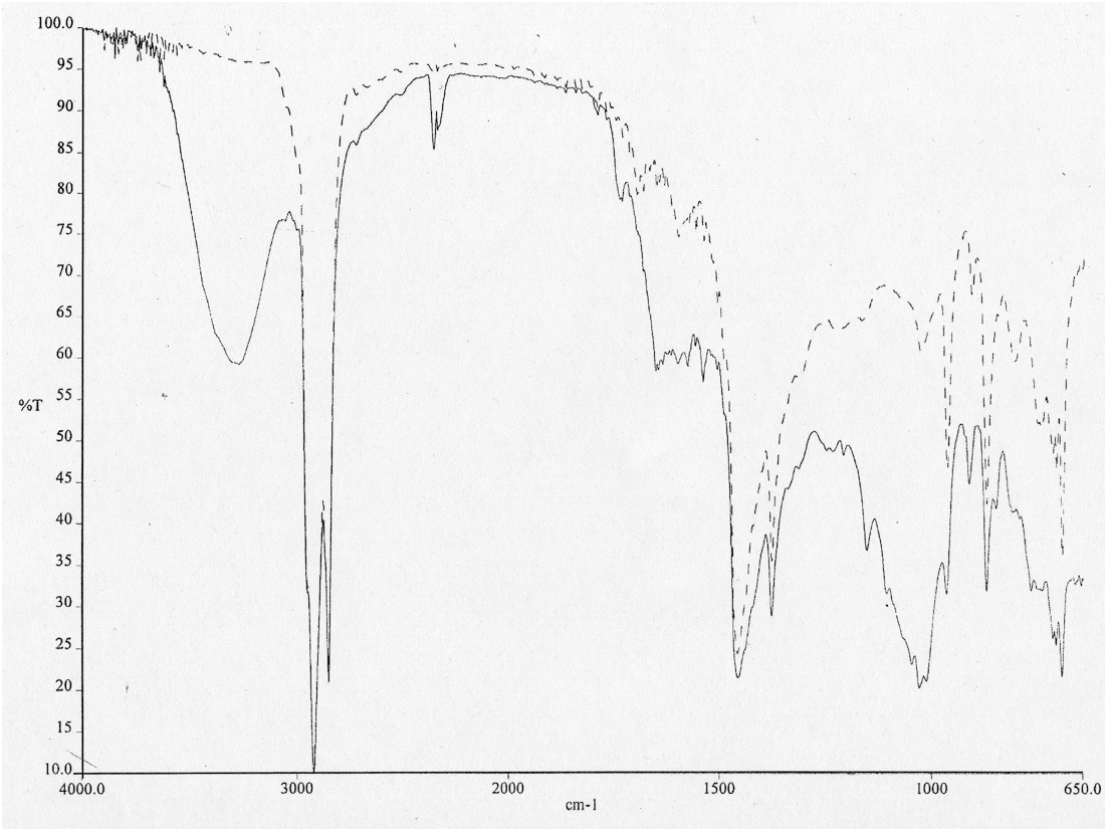
Sample C (BUR), top surface.



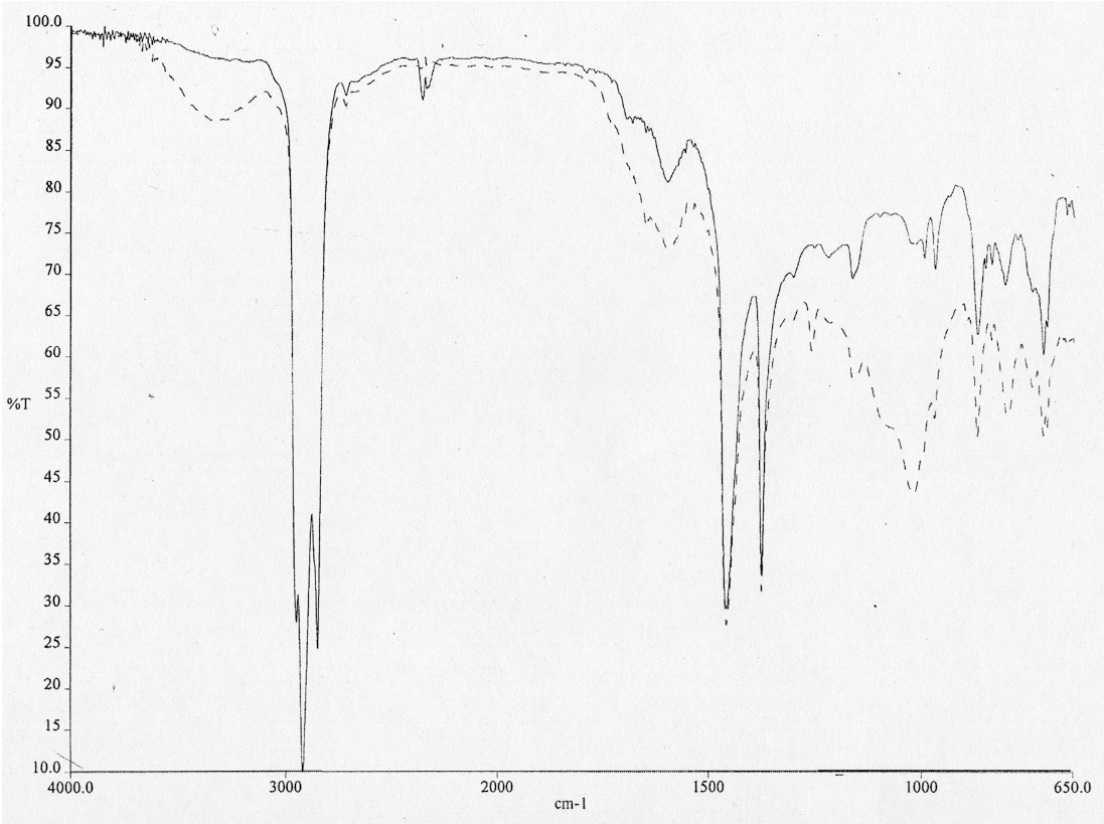
Sample D (BUR), top surface.



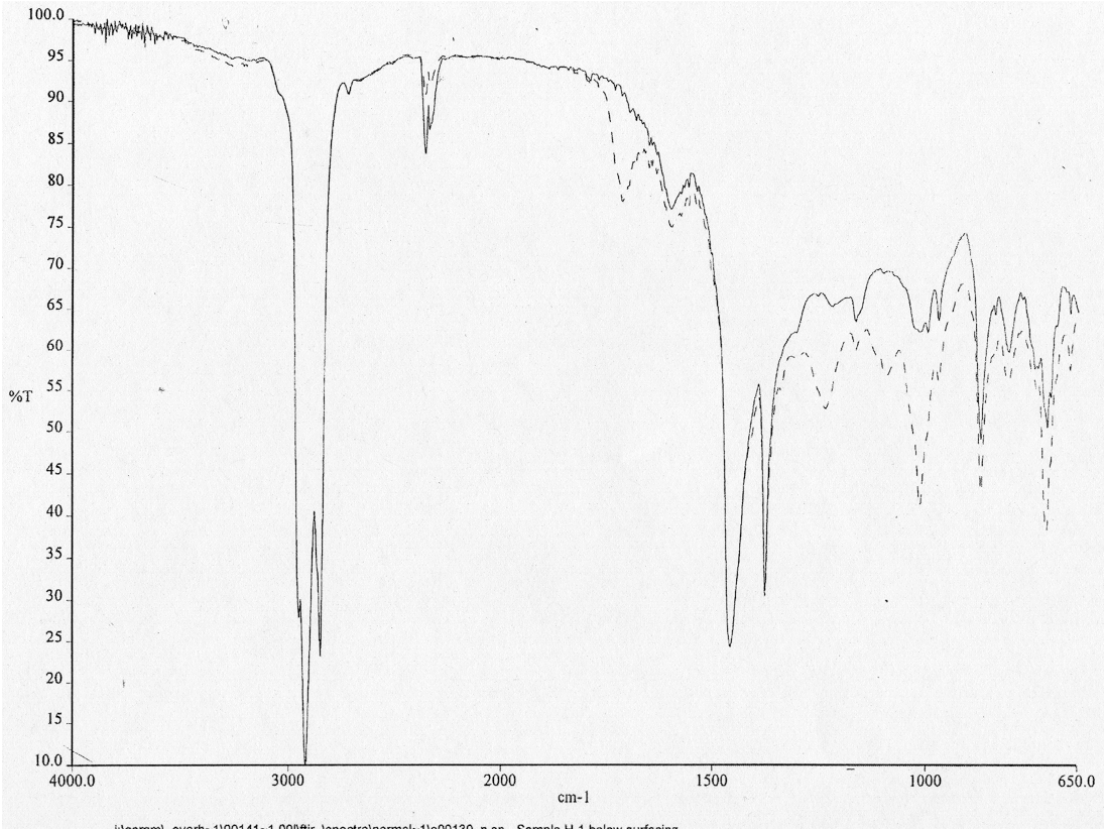
Sample E (SBS MB), granular surfacing removed.



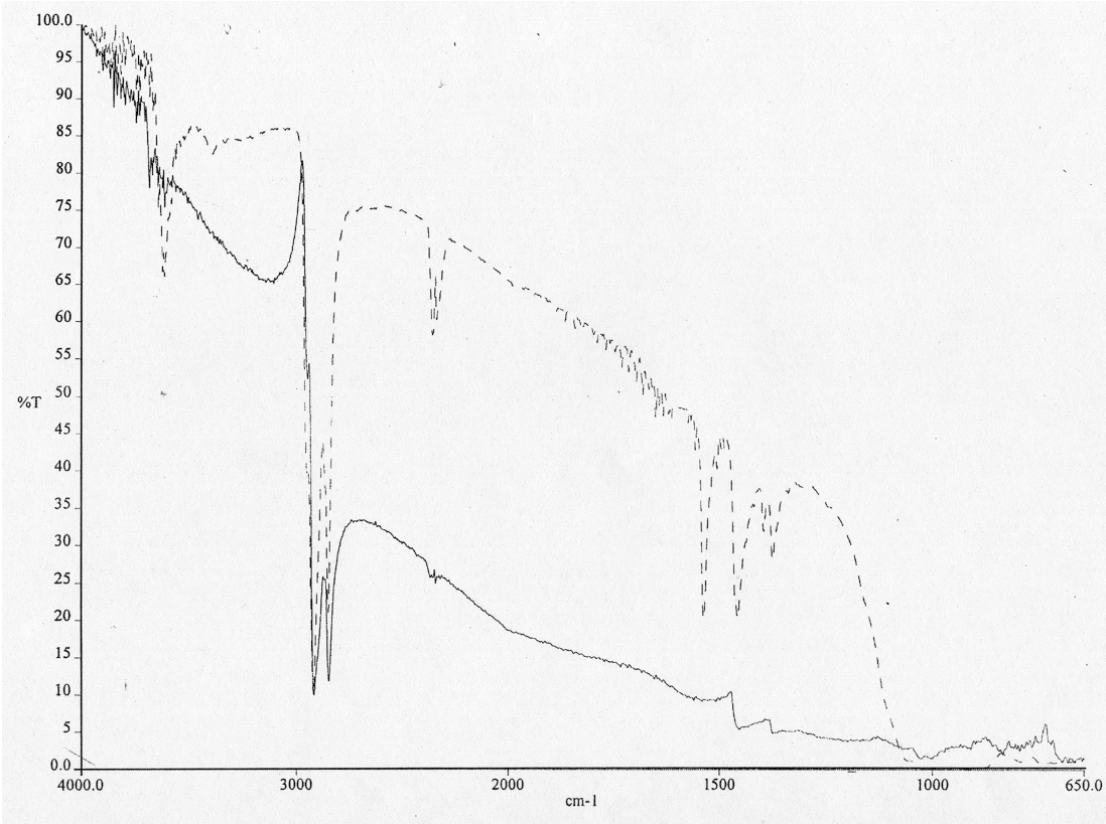
Sample F (SBS MB), granular surfacing removed.



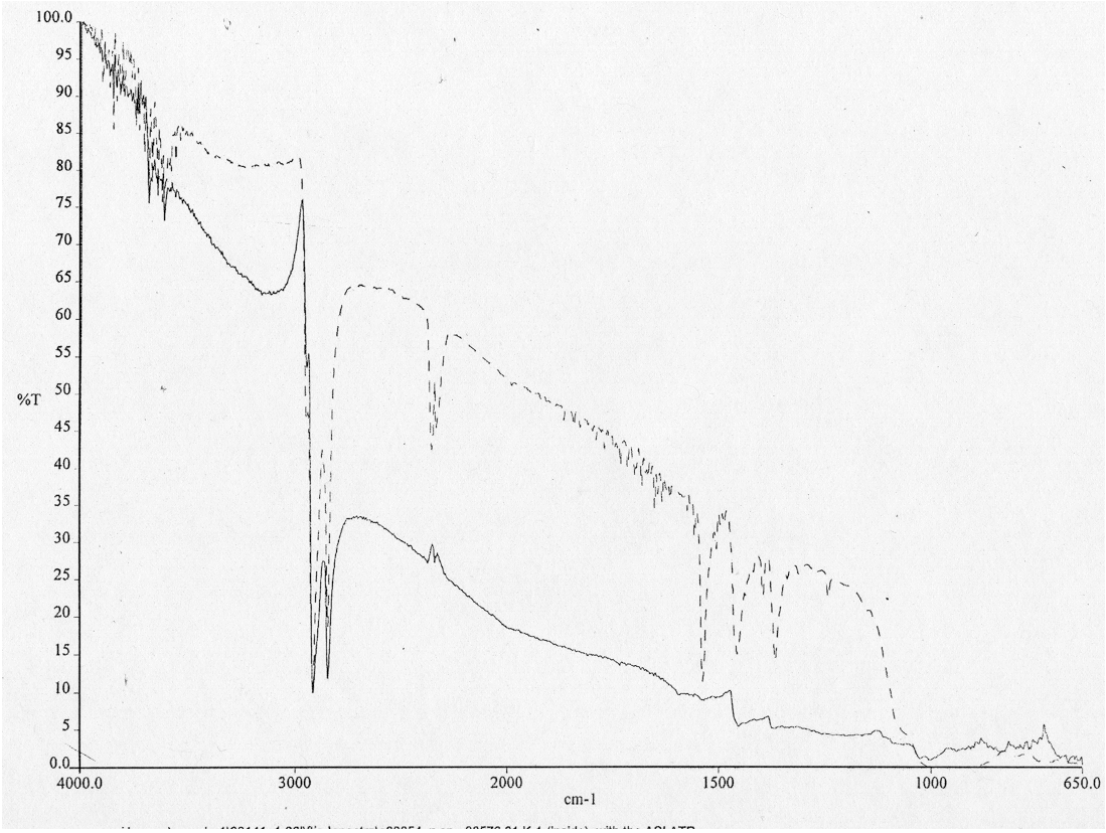
Sample G (APP MB), granular surfacing removed.



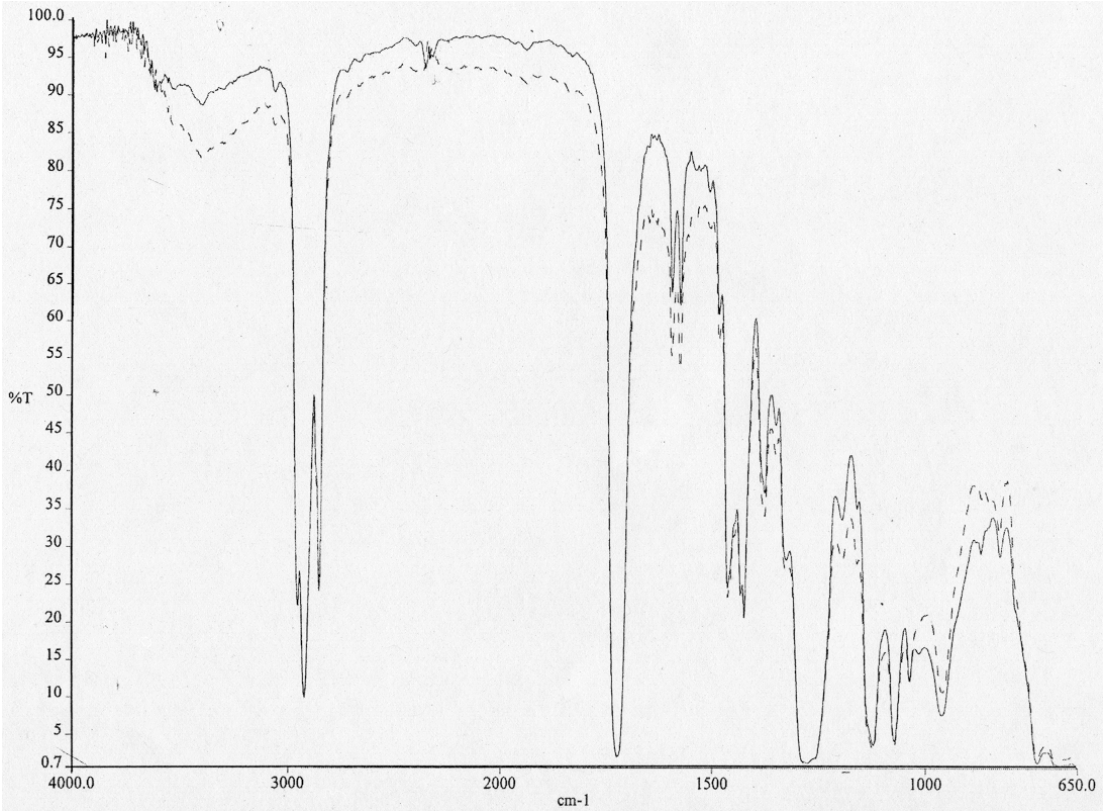
Sample H (APP MB), granular surfacing removed.



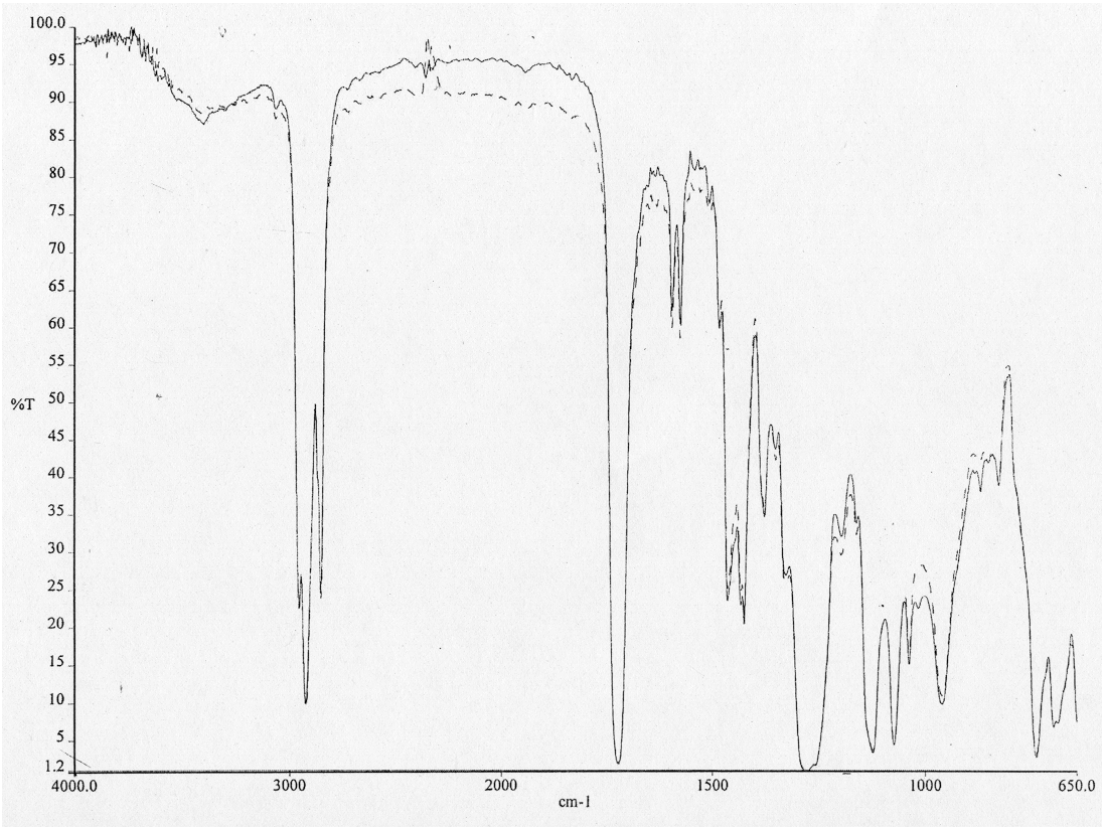
Sample J (EPDM).



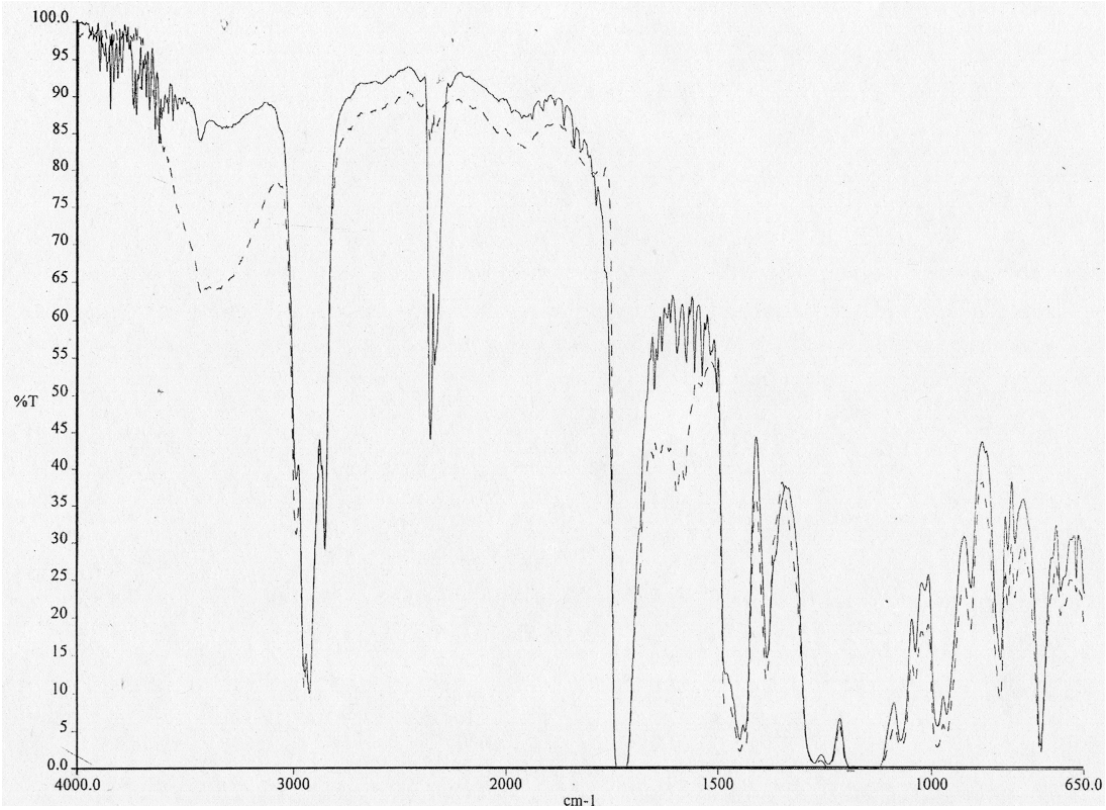
Sample K (EPDM).



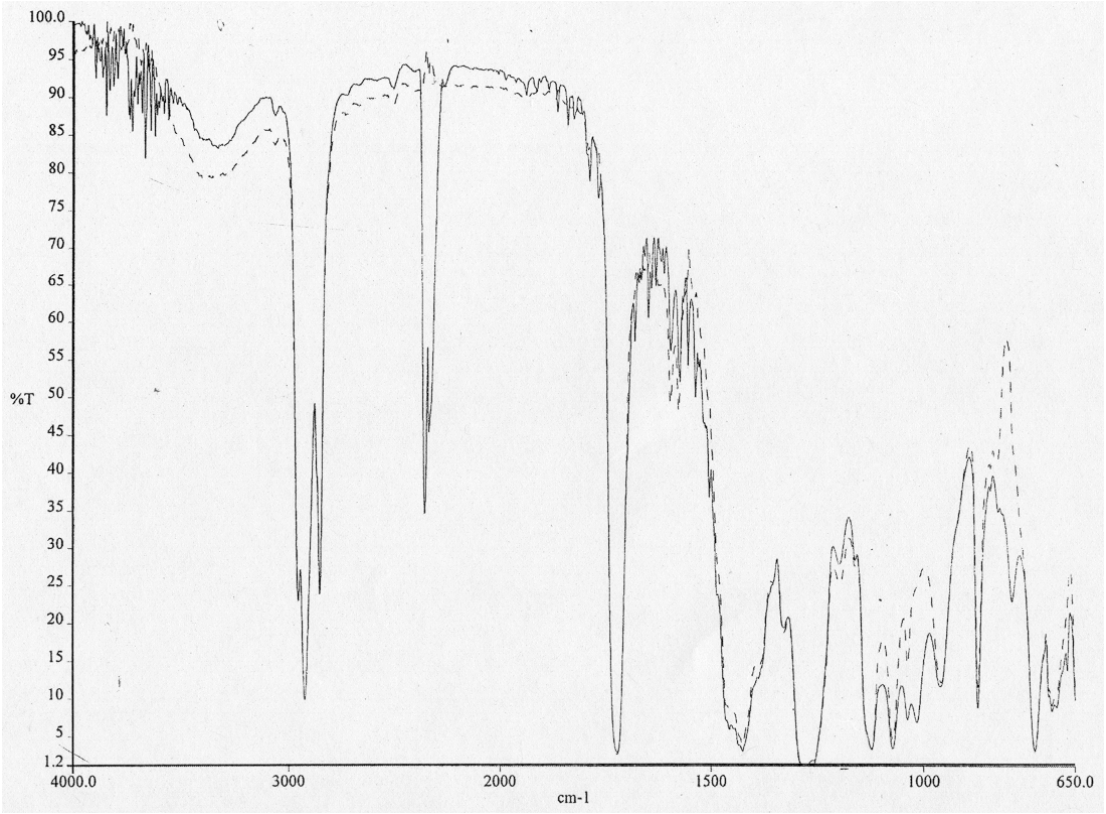
Sample L (PVC), top surface.



Sample L (PVC), bottom surface.



Sample M (PVC), top surface.



Sample M (PVC), bottom surface.

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14. ABSTRACT

The average service life of roofing membranes used in low-slope applications on U.S. Army buildings is estimated to be considerably shorter than the industry-presumed 20-year design life, even when installers carefully adhere to the latest guide specifications. This problem is due in large part to market-driven product development cycles, which do not include time for long-term field testing. To reduce delivery costs, contractors may provide untested, inferior membranes in place of ones proven satisfactory in long-term service. Federal procurement regulations require that roofing systems and components be selected according to desired properties and generic type, not brand name. The problem is that a material certified to have satisfactory properties at installation time will not necessarily retain those properties in service.

The overall objective of this research is to develop a testing program that can be executed in a matter of weeks to adequately predict a membrane's long-term performance in service. This report details accelerated aging tests of 12 popular membrane materials in the laboratory, and describes outdoor experiment stations set up for long-term exposure tests of those same membranes. The laboratory results will later be correlated with the outdoor test results to develop performance models and predictive service life tests.

15. SUBJECT TERMS
roofing membranes, service life, military facilities, roofing material, materials performance, predictive maintenance

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