LABORATORY EVALUATION OF EPDM ROOF MEMBRANES: A 17-YEAR HISTORY OF PERFORMANCE

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Single-ply rubber sheets, based upon ethylene propylene diene terpolymers (EPDM), have steadily increased in usage for roof membranes over the past 20 years. The use of EPDM has significantly advanced the technology of roofing, particularly for large, low-slope, commercial buildings. This paper summarizes the physical properties of membrane samples obtained from 45 EPDM roofs that range from three to 17 years of age, and compares the data to laboratory heat aging and xenon-arc accelerated weather testing. Basic physical properties such as tensile strength and elongation are reported for all samples. More sophisticated, time consuming tests, such as brittleness temperature, were performed on some of the samples. The roof aged sheet properties are evaluated against established standards for elastomeric sheets.

KEYWORDS

Appearance, brittleness temperature, differential scanning calorimetry (DSC), elongation, ethylene propylene diene terpolymers (EPDM) roof membranes, glass transition temperature, hardness, tear resistance, tensile strength.

INTRODUCTION

EPDM polymer became commercially available in 1963, and by 1965 sheets were manufactured from formulations consisting of EPDM polymer, carbon black, process oil, zinc oxide and curing agents. Sheets made from early formulations (mid-1960) had excessive shrinkage due to the use of process oil that was too volatile. When the sheet was heated by the sun, some of the oil left the rubber and shrinkage occurred. The pioneers of EPDM formulations for roofing and waterproofing quickly learned to use very low volatility oil that would remain in the sheet and not cause long-term oil loss which induced shrinkage.

By 1970, the formulation chemistry and manufacturing technology was established to produce EPDM sheets that had the proper balance of physical and chemical characteristics suitable for roof membranes. Not only was it necessary to have desirable properties initially engineered into the membrane, but the properties had to be maintained above minimum levels for satisfactory long-term performance.

All roofing materials are affected by the combined influence of water, solar ultraviolet radiation, heat, ozone and thermal cycling. Biological attack, atmospheric pollution and physical damage are additional factors that can diminish the performance of the roofing membrane. Roof system design can magnify or minimize the exposure of the roof membrane to environmental stresses that cause deterioration and eventual failure of the roof system. The combined affect of all these factors is so complex that even the most rigorous laboratory test program alone cannot completely predict the long-term performance of roofing membranes and system components.

An essential component of membrane performance evaluation for research purposes is the periodic inspection, sampling and laboratory testing of actual field aged roof sheet. Samples must be collected from all system types, in hot and cold climates. Unusual exposure conditions must be examined and taken into consideration to accurately assess the condition of the membrane.

Studies relating actual outdoor, real-time exposure to laboratory accelerated weathering have shown that EPDM rubber sheets have outstanding long-term weather resistance, although certain physical properties do change as the exposure period increases. Even though EPDM has earned a reputation for its weatherability, some questions remain to be answered:

- What important physical properties change upon exposure?
- How do aged properties compare with ASTM D 4637[1] new material standards and the Midwest Roofing Contractors Association (MRCA) ME-20[2] performance criteria for elastomeric membranes?
- Can the age of an EPDM roof be determined by physical property evaluation, surface appearance or thermal analysis?
- How do aged physical properties of EPDM membranes in exposed systems compare to membranes in protected systems?

This paper will provide some insight on the answers to these questions. It must be emphasized that the data presented herein is based upon long-term exposure of Carlisle SynTec Systems formulated sheet.

THE TEST PROGRAM

Membrane samples were cut from 45 roofs representing 13 states. The samples were obtained from standard roofs (not experimental) at random by persons unaware of the test protocol. The buildings are hospitals, colleges, schools, laboratories, distribution centers, hotels, churches, stores, banks, manufacturing facilities and offices. The roof systems are fully adhered (18), mechanically fastened (4), ballasted (20) and "insulated" membrane assembly (3).

The samples were tested for tensile strength and ultimate elongation in the machine direction using ASTM Test Method D 412.[3] The results are shown in Figures 1 through 4. The tear resistance was determined in the machine direction using ASTM Test Method D 624,[3] and the results are shown in Figures 5 and 6. Membrane hardness, determined with a Shore A Durometer as specified by ASTM Test Method D 2240,[3] is shown in Figures 7 and 8.

Most of the samples were analyzed using thermogravimetric analysis (TGA), and some of the samples were tested for glass transition temperature using differential scanning calorimetry (DSC). Both techniques are forms of thermal analysis in which a physical property of a substance is measured as a function of temperature. Examples of physical properties include mass, temperature, enthalpy and dimension.

TGA measures the change in mass as a function of temperature. The sample is heated at a fixed rate in a controlled furnace atmosphere. As the sample is heated, components begin to volatilize. The resulting mass change versus temperature curve (also called a thermogram) provides valuable information on the thermal stability and composition of the material. It is important to remember that most of the information obtained from the TGA is empirical in nature—that implies it is dependent on instrument parameters such as heating rate and atmospheric conditions around the sample. A standard thermogram is shown in Figure 10. It can be seen that as the sample is heated in a nitrogen atmosphere, polymer and oil components volatilize simultaneously. After this step is completed, the atmosphere is switched to air and combustion of any other organic material occurs. In the case of black EPDM rubber compounds, this component is usually carbon black. At the end of the test, an ash remains which can be used for elemental analysis to determine if the membrane contained ingredients like zinc oxide, titanium dioxide, talc, clay, mica, etc. Comparison of scans of unaged and aged membrane gives us the ability to monitor how the materials composition is affected by long-term weathering. For instance, oil or plasticizer loss can be monitored and subsequently correlated to changes in physical properties.

Differential scanning calorimetry (DSC) measures the heat energy emitted or absorbed by the sample as the temperature is increased at a controlled rate. For rubber, it is most useful for determining phase changes and the glass transition temperature. The glass transition temperature is the midpoint of the temperature range where the sample changes from a rubbery to a hard and relatively brittle material. Five samples were subjected to DSC analysis and the glass transition temperature was compared to the brittleness temperature as determined by ASTM Test Method D 746.[4] An example of a DSC analysis is shown in Figure 11.

PHYSICAL PROPERTY TEST RESULTS

The physical property test results were separated into two major groups; values for exposed membranes and "protected" membranes. Exposed membranes were taken from either fully-adhered roof systems or mechanically-fastened systems. The term "exposed" means that the membrane was not protected by design from solar radiation. Exposed membrane properties are shown in Figures 1, 3, 5 and 7. Each bar represents a separate roof and the values for tensile strength, elongation, tear resistance and hardness match position by position through each bar graph. As an example, the three-year old roof had a tensile strength of 10.6 MPa, an elongation of 530 percent, a tear resistance of 42.0 kN/m and a hardness of 60.

For this paper, "protected" membranes are defined as ballasted or insulated (also known as protected membrane roofs). Figures 2, 4, 6 and 8 show protected membrane properties. The ballasted systems have some protection from solar radiation depending upon the ballast coverage density, and the insulated membranes are protected by insulation/ballast.

Tensile Strength

The tensile strengths ranged from 10.5 to 14.8 MPa for exposed membranes and 11.1 to 13.7 MPa for protected membranes (see Figures 1 and 2). The ASTM minimum requirement for new sheet is 9.0 MPa and the MRCA minimum performance requirement is 6.0 MPa. All aged sheet tensile strengths exceed ASTM and MRCA requirements for new EPDM membrane.

Elongation

The ultimate elongations ranged from 230 to 530 percent for exposed membranes and 290 to 480 percent for protected membranes (see Figures 3 and 4). The ASTM minimum requirement for new sheet is 300 percent and the MRCA minimum performance requirement is 250 percent. All sheet ultimate elongations, except the 17-year old exposed membrane (230 percent), exceed the MRCA performance requirement for elongation.

Tear Resistance

Tear resistance ranged from 42.0 to 57.8 kN/m for exposed membranes and 45.5 to 59.5 kN/m for protected membranes (see Figures 5 and 6). The ASTM minimum requirement for new sheet is 26.0 kN/m and the MRCA performance requirement is 21.0 kN/m. All aged sheet tear resistances exceed ASTM and MRCA requirements.

Hardness

Hardness ranged from 60 to 81 for exposed membranes and 62 to 76 for protected membranes (see Figures 7 and 8). There are no ASTM or MRCA requirements for hardness. Although there are no standard requirements for hardness, it is an important gauge to measure the cure state of rubber articles. As EPDM sheets weather, the hardness generally increases. The aged hardness can be compared to the original unaged hardness.

Brittleness Temperature

The brittleness temperatures ranged from −62°C for unaged sheet to −70°C for aged membrane (see Figure 9). The ASTM minimum requirement for new sheet is −45°C and the MRCA performance requirement is −40°C. All samples tested passed the low temperature requirements. The lower the brittleness point, the better the membrane is for low temperature flexibility.

Glass Transition Temperature

The glass transition temperature remained at −49°C for all samples; aged and new. No standard specification exists for glass transition temperature.

Appearance

Photographs were taken of new and aged membranes and enlarged to 2X. Figure 12 shows the surface appearance of protected EPDM membranes from five, eight and 10-year old roofs compared to new membrane. Figure 13 is a photograph of exposed membranes from five, nine and 17-year old roofs with a new sample for comparison. None of the membrane samples had any visual indication of weather degradation (no cracking or crazing) other than the usual very thin black layer of powder observed on most aged EPDM roofs.

TYPICAL BACKGROUND LABORATORY DATA FOR EPDM MEMBRANE

EPDM formulations that are sulfur cured and contain carbon black for UV protection are generally more affected by heat aging than any other single factor (UV, ozone, water, etc.) during weathering. It is common for exposed black roof membranes to be at elevated temperatures (60° to 70°C and higher) during warm weather daylight hours. The effects of heat aging are accelerated in the laboratory by increasing the temperature to reduce the test time to practical periods. The most severe standard aging temperature for any roof membrane is 115°C, as specified by ASTM D 4637 and as an alternate temperature in ME-20.

The physical properties of EPDM membranes follow predictable trends during heat aging. The tensile strength increases after short-term aging (i.e., one week at 115°C), and then gradually decreases to about 8 MPa at 10 weeks of aging.

Figure 14 shows a typical response of tensile strength to aging at 115°C out to 10 weeks accumulated time. Ten weeks of heat aging at 115°C is approximately equivalent to 20 years of 65°C membrane temperatures for eight hours every day.

Figure 15 shows the response of ultimate elongation to heat aging. The elongation has the highest rate of reduction during the first week of heat aging at 115°C and has a very gradual downward trend from one week through the 10th week of aging.

Hardness, like elongation, has the most change due to heat aging during the first week. After the first week, the hardening process proceeds at a much slower rate. The hardness increase from heat aging is shown in Figure 16.

In a study[5] sponsored by the Rubber Manufacturers Association (RMA), black EPDM membrane was exposed to various types of accelerated weathering. Both the control (known formulation) and commercial sheet (formulation unknown) followed the same general trends as described above for laboratory heat aging. Laboratory xenon-arc exposure data from the RMA study is an example of the physical property changes that occur upon exposure to ultraviolet radiation, heat and water spray. Figure 17 shows the increase, then reduction in tensile strength; and the short-term drop, then gradual reduction of elongation.

DISCUSSION AND CONCLUSIONS

It is possible to note some general conclusions or trends that are evident from the exposure data by comparing the field aged samples with laboratory aged samples and original typical physical properties. Figures 18 through 21 show actual physical properties of new EPDM membrane produced during the fourth quarter of 1983. The 1983 data is used as typical data for the purpose of this discussion. The graphs (Figures 18 to 21) were produced in 1983 and are in non-SI units. The data, converted to SI units, is summarized below:

Typical Original Membrane Properties

Property	Mean	Most values fall between
Tensile strength (MPa)	11.7	11.4—12.2
Elongation (%)	500	450—550
Tear resistance (kN/m)	40.3	36.8—42.0
Hardness (Shore A)	56	55—58

Important Physical Properties Do Change Upon Exposure

The physical properties of the samples taken from the roofs show a general increase in tensile strength, tear resistance, and hardness, and a reduction in ultimate elongation as compared to typical original, unaged properties. This can be seen by comparing Figures 1 through 8 with the original sheet properties shown above. The brittleness temperature actually improves upon roof exposure even though the membrane hardness increases. This is shown in Figure 9.

If the property values from Figures 1 through 8 are compared to what will occur at some point in time with heat aging (Figures 14, 15 and 16) and xenon-arc weathering (Figure 17), all membranes except the 17-year sample are still in the early years of their service life. The 17-year old sample has approached middle age, although the tensile strength is still at a high value. Figures 1 through 9 do not show any particular trend in the properties as the roof age increases, which is contrary to the expected reduction in tensile and elongation during laboratory accelerated weathering. Apparently, more roof aging will be required to begin to show the slow reduction in physical properties expected from the lab aging.

Most Aged Sheets Exceed the ASTM and ME-20 Requirements for New Membrane

Eighty-seven percent of the samples exceed ASTM and ME-20 requirements for new membrane. All of the samples except the 17-year old membrane exceed ME-20 performance requirements. The 17-year old sample did not meet ME-20 because its elongation was 230, below the 250 percent requirement for new membrane.

The Age of an EPDM Roof Cannot Be Precisely Determined by Physical Property Evaluation, Surface Appearance or Thermal Analysis

It can be easily seen from Figures 1 through 9 that there is no correlation between physical properties and the age of the membrane, at least from age four through 12 years. None of these samples have reached the point where the physical properties are significantly different from the rest of the series that a conclusive age can be ascertained.

Surface appearance is of little value for determining the age of the membrane. Most of the protected membrane surfaces look like new sheet after the dust was removed. The exposed membranes all had a black film also called "black chalk" that is seen on practically all weathered EPDM surfaces. The amount of the black film did not increase as the membrane age increased. Perhaps the film is washed away so that it does not accumulate as the membrane gets older. Reduction in thickness may be a technique for determining exposed membrane age, but no data was available for this study because exact original, unaged thicknesses were not accessible.

Thermal analysis was also of little benefit for age determination. The glass transition temperature as determined by differential scanning calorimetry remained at −49°C regardless of membrane age, although the brittleness temperature tended to improve with age.

Thermogravimetric analysis (TGA) allows the authors to quantify the composition of a rubber membrane. From the standard TGA scan, in conjunction with solvent extraction, the content of various components of a rubber compound can be determined. This information can be compared with the original membrane formulation and any compositional changes can be determined. Initially it was believed that the amount of oil loss upon weathering would increase with the age of the membrane. The data did not show this to be the case. There was no correlation between years exposed in the field and oil loss (correlation coefficient $r = 0.49$).

Figure 22 is a TGA scan of a 5-year old roof in Pennsylvania and Figure 23 is a scan of a 10-year old roof in Illinois. The solid line curves practically match showing that there is no correlation between age and TGA scan. The use of TGA as a means to determine the age or to evaluate the performance of EPDM is even more limited if original formulations are unknown. Formulations are usually kept confidential by manufacturers, so TGA analysis performed on aged roof samples by non-manufacturers would be of limited value.

The Long-Term Weatherability of EPDM Is Not System Dependent

Ballast is of no significant value for protecting the membrane from heat or ultraviolet radiation; at least for the first 15 years of roof exposure. The EPDM does not need system protection from the elements, and average aged physical properties are only slightly improved when exposed versus protected system aged properties are compared. Using the data from Figures 1 through 8, the properties for all eight and nine-year old membranes were averaged and are shown below.

Averages of Eight and Nine-Year Old Membrane Physical Properties

Property	Exposed membranes	Protected membranes
Tensile strength (MPa)	12.0	12.4
Ultimate elongation (%)	325	370
Tear resistance (kN/m)	50.1	50.6
Hardness (Shore A)	70	70

It May Require More Than 50 Years of Exposure for EPDM to Drop Below MRCA ME-20 Performance Requirements for Aged Sheet

A question that is often asked and usually avoided is, "Just how long will the single-ply membrane last?" The heat aging data shown in Figures 14 and 15 can be used to predict the point at which tensile strength and elongation will drop below MRCA ME-20 requirements for aged membrane.

The ME-20 aged minimum values are 5.5 MPa for tensile strength and 200 percent for ultimate elongation. The data shows the elongation will drop below the 200 percent requirement after seven weeks aging at 115°C.

The eight and nine year data average for exposed systems is 325 percent elongation which occurs on the heat aging curve at approximately one week. The problem becomes one of relating eight and nine year field data equivalent to one week heat aging to how many years of field exposure will be required to reach the seven week aged properties. Conservatively, it will take an average of 56 years (8x7) for fully exposed EPDM to drop below the 200 percent elongation, and the tensile strength will remain above 5.5 MPa. Even when the membrane reaches these minimums, it probably will not fail its function as a watertight sheet. It is important to note that a watertight roof is also dependent on the satisfactory performance of other system components such as field fabricated seams, flashing, pipe seals, etc.

RECOMMENDATIONS FOR ADDITIONAL WORK

The usual result of most research is that more questions are generated that require additional research work. This research is no exception. Following are questions that need to be answered:

- What can be done to estimate the age of an EPDM roof?
- Does the increase in membrane hardness over time improve system puncture resistance?
- Do white and reinforced EPDM membranes have the same long-term weathering characteristics as black non-reinforced EPDM evaluated in this study?
- Why does brittleness temperature improve upon aging?
- Do EPDM roofs fail as a watertight barrier when certain physical properties fall below established criteria?

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The authors also express their appreciation to the Management of Carlisle SynTec Systems for providing the resources for this research.

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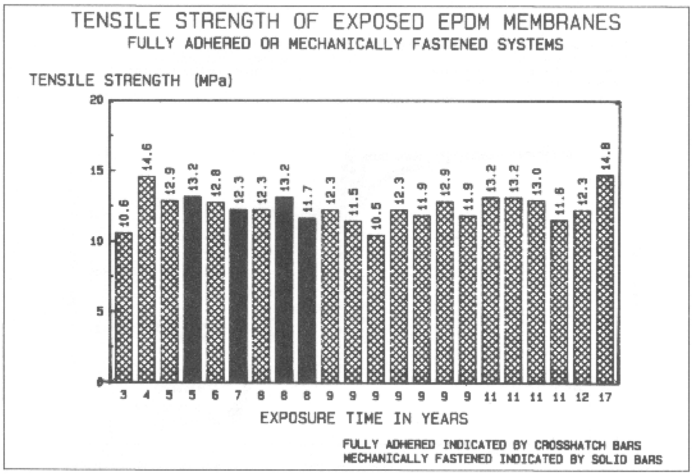

Figure 1 *Tensile strength of exposed EPDM membranes—fully-adhered or mechanically-fastened systems.*

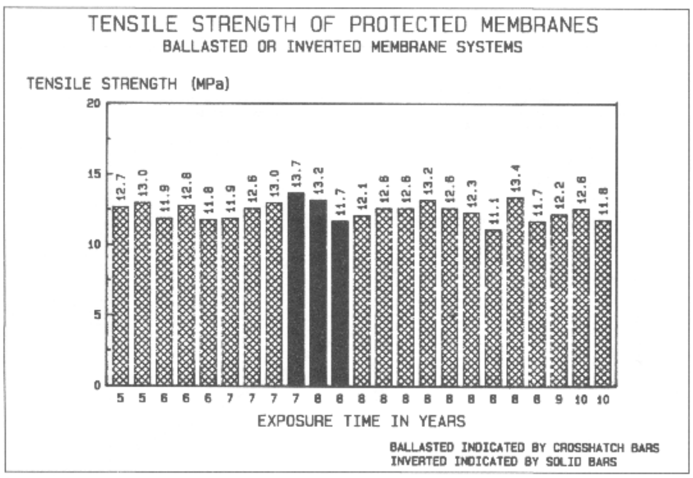

Figure 2 *Tensile strength of protected membranes—ballasted or insulated membrane systems.*

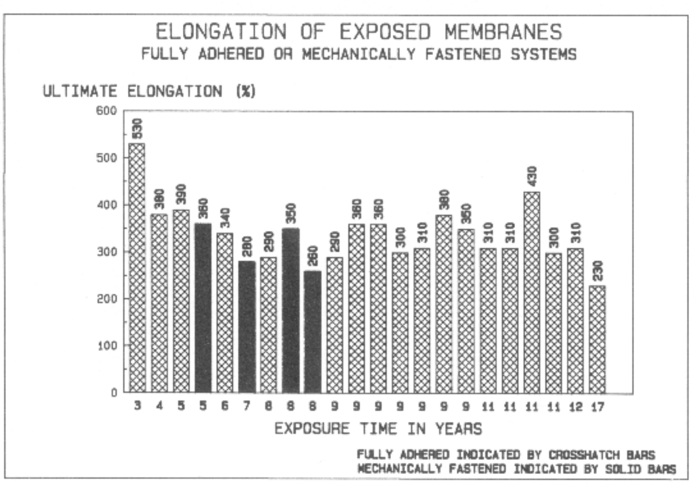

Figure 3 *Elongation of exposed membranes—fully-adhered or mechanically-fastened systems.*

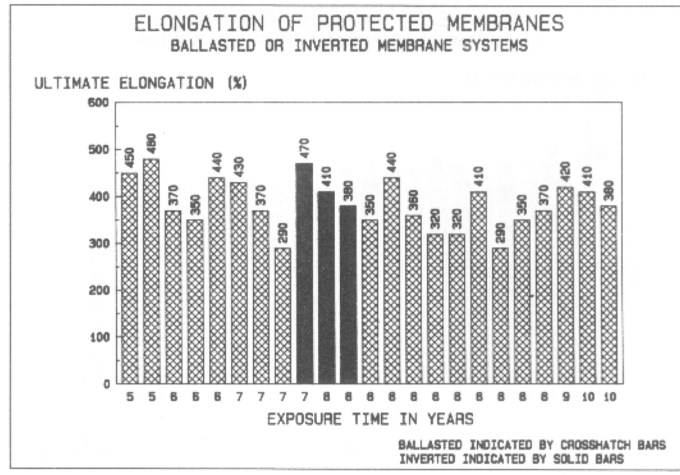

Figure 4 *Elongation of protected membranes—ballasted or insulated membrane systems.*

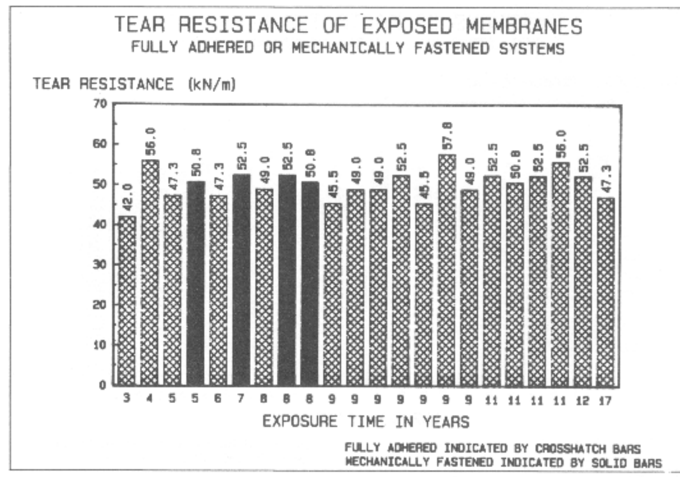

Figure 5 *Tear resistance of exposed membranes—fully-adhered or mechanically-fastened systems.*

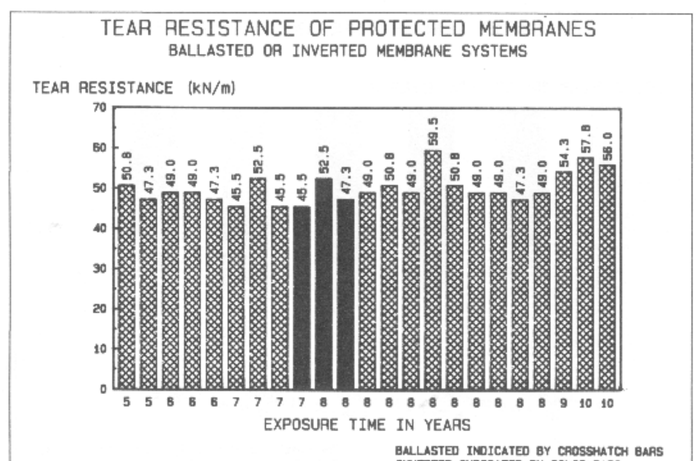

Figure 6 *Tear resistance of protected membranes—ballasted or insulated membrane systems.*

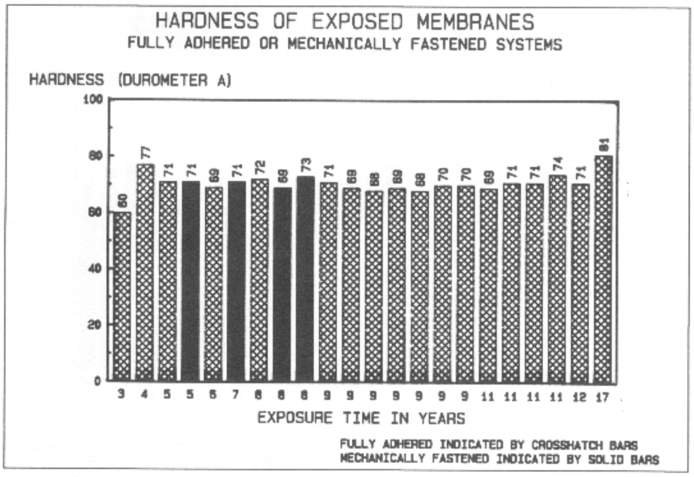

Figure 7 Hardness of exposed membranes—fully-adhered or mechanically-fastened systems.

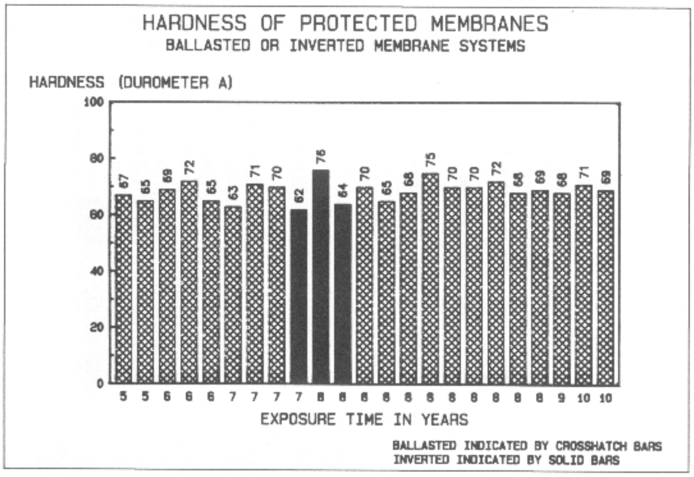

Figure 8 Hardness of protected membranes—ballasted or insulated membrane systems.

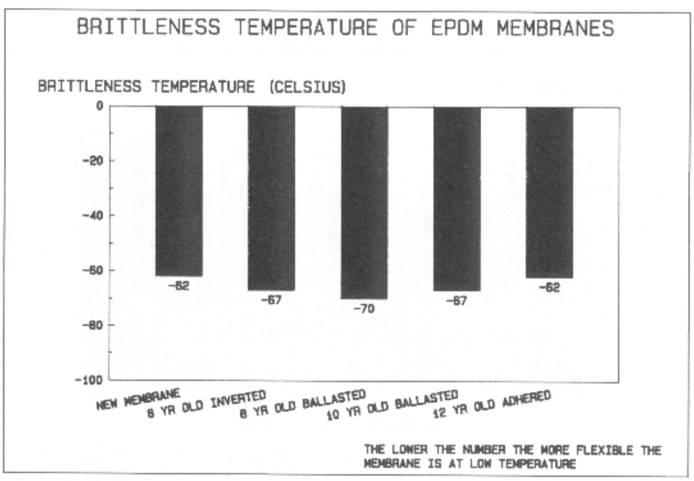

Figure 9 Brittleness temperature of EPDM membranes.

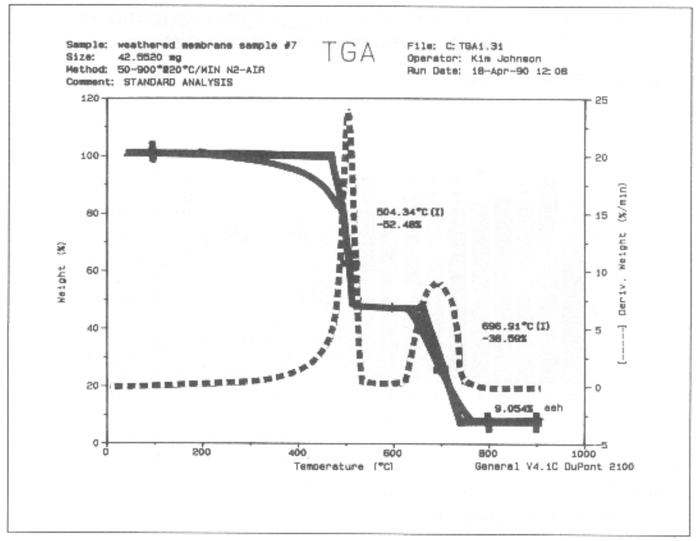

Figure 10 TGA—weathered membrane sample #7.

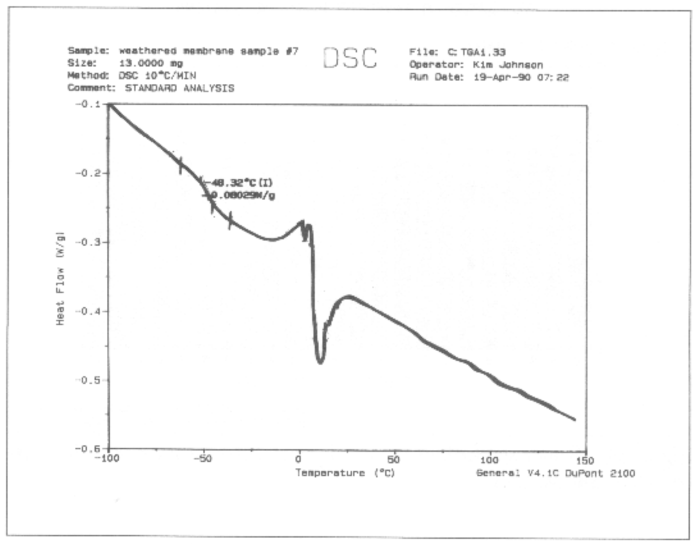

Figure 11 DSC—weathered membrane sample #7.

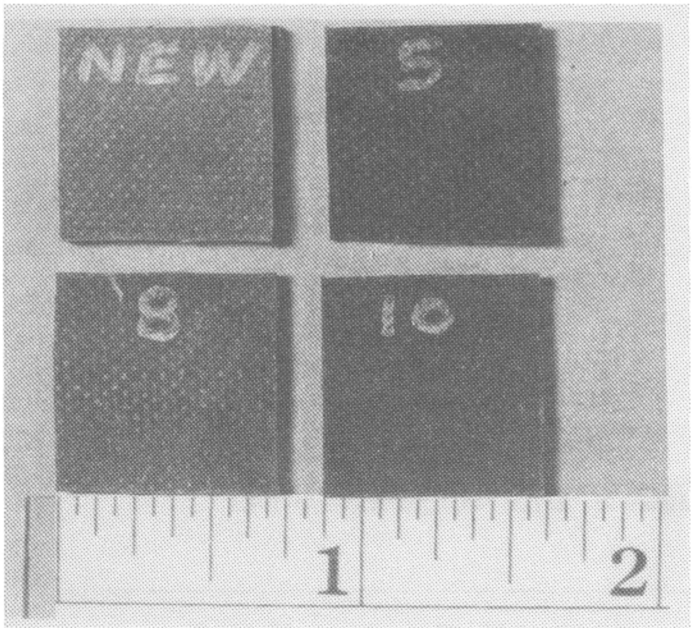

Figure 12 Surface appearance of protected EPDM membranes from five, eight and 10-year old roofs compared to new membrane.

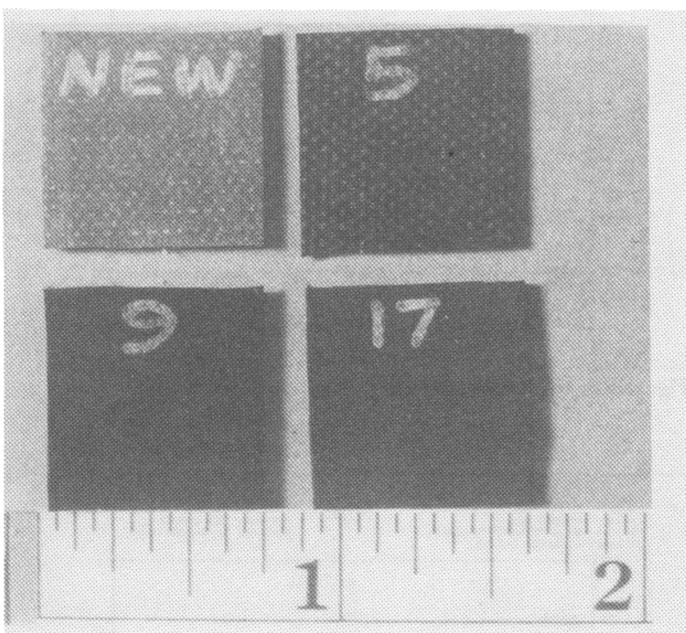

Figure 13 Surface appearance of exposed membranes from five, nine and 17-year old roofs compared to new membrane.

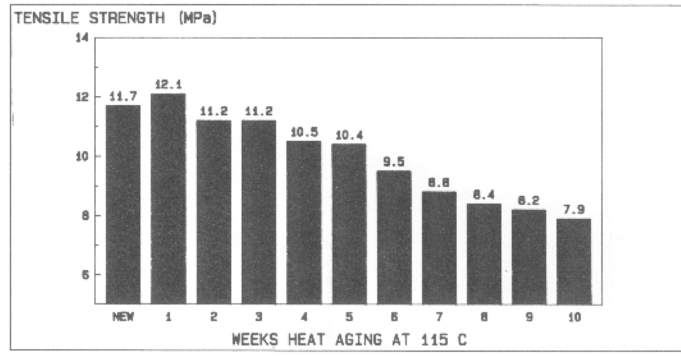

Figure 14 EPDM tensile strength after heat aging—10-week study.

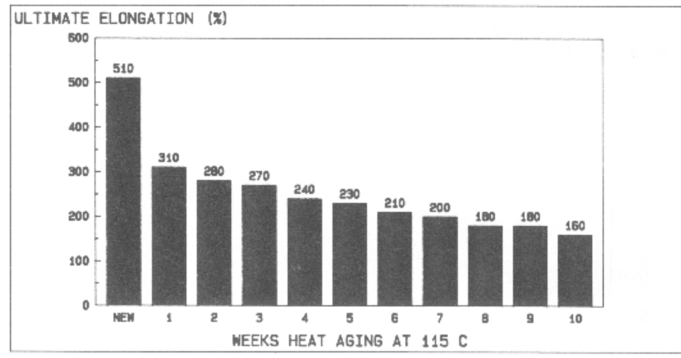

Figure 15 EPDM ultimate elongation after heat aging—10-week study.

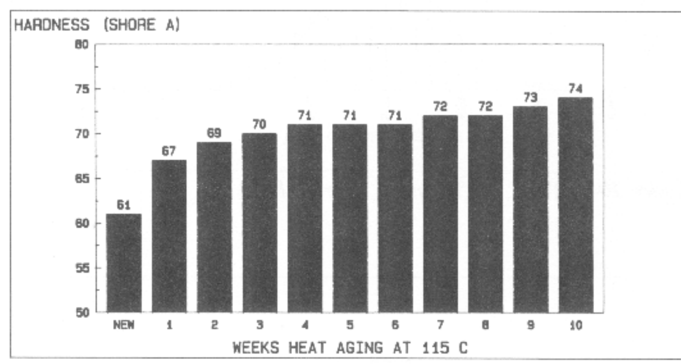

Figure 16 EPDM hardness after heat aging—10-week study.

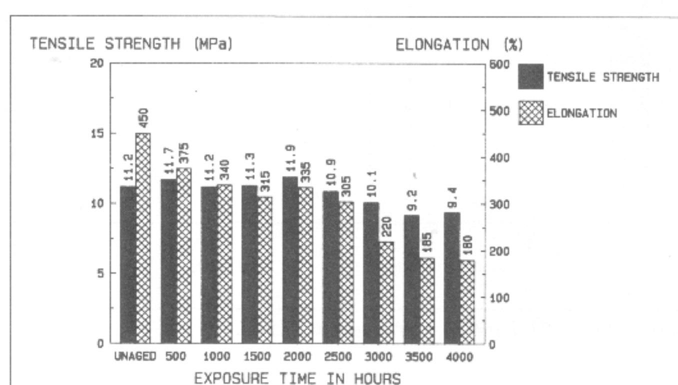

Figure 17 Properties of EPDM after xenon-arc exposure.

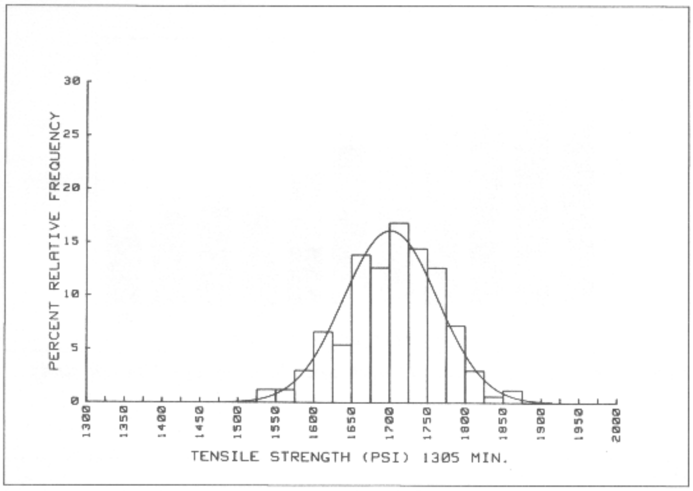

Figure 18 *EPDM (465), fourth quarter 1983.*

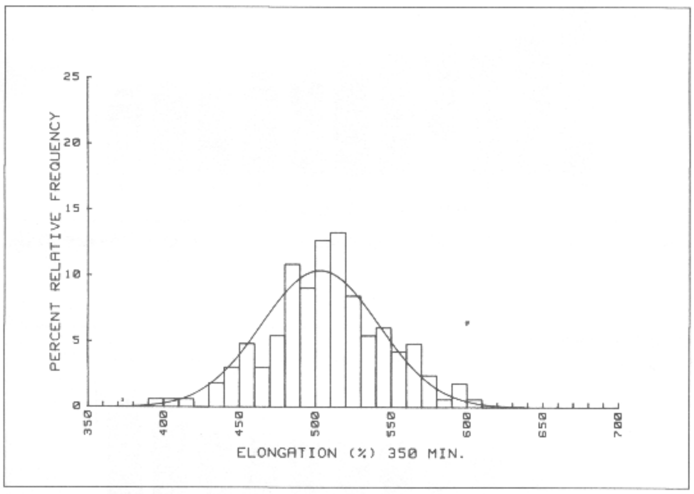

Figure 19 *EPDM (465), fourth quarter 1983.*

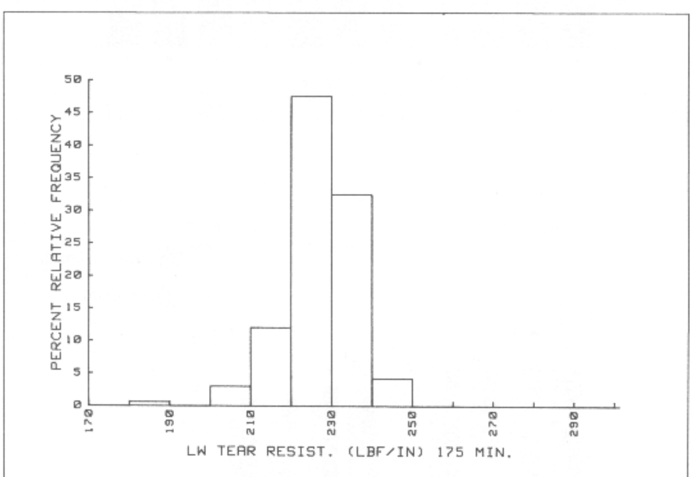

Figure 20 *EPDM (465), fourth quarter 1983.*

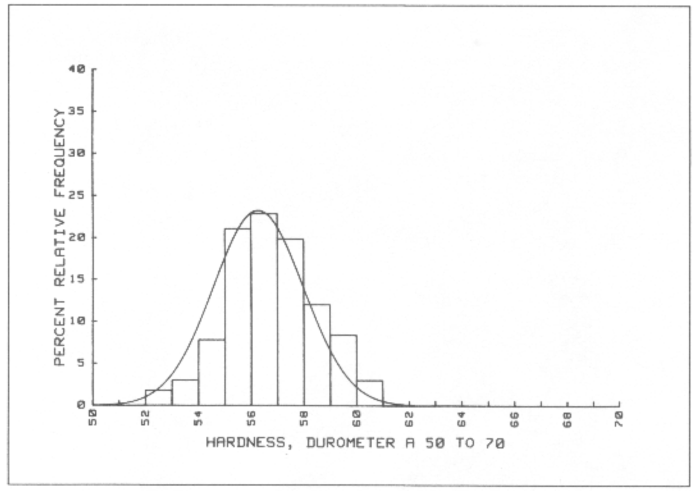

Figure 21 *EPDM (465), fourth quarter 1983.*

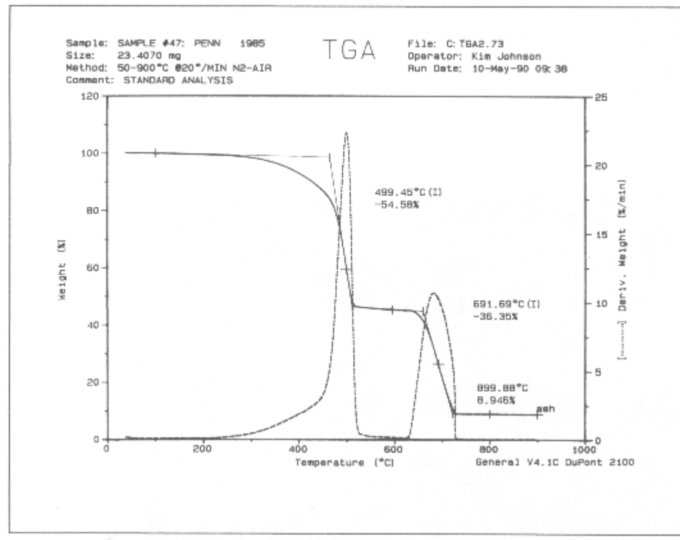

Figure 22 *TGA—sample #47, Pennsylvania 1985.*

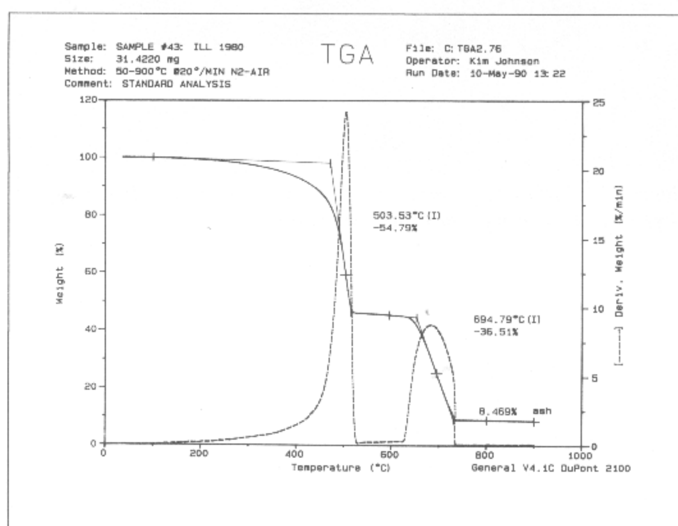

Figure 23 *TGA—sample #43, Illinois 1980.*