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SHATTERING OF UNREINFORCED PVC ROOF MEMBRANES: PROBLEM PHENOMENON, CAUSES AND PREVENTION

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This paper reports on the phenomenon of shattering of unreinforced PVC roof membranes. To further understand the problem and to provide data for the assessment of existing in-service unreinforced PVC roofs, samples of unshattered (unweathered) and shattered membranes were studied using dynamic mechanical analysis. It was found that the glass transition temperature, T_g, may be useful in explaining the shattering phenomenon. Furthermore, the T_g values can easily be obtained using dynamic mechanical analysis.

Recommendations to avoid shattering of existing unreinforced membranes (including the use of thermal analysis to evaluate shatter potential) are presented, along with recommendations regarding revisions to ASTM D 4434. Current generation reinforced PVC roof membranes are also discussed.

KEYWORDS

ASTM D 4434, DMA, dynamic mechanical analysis, glass-transition temperature, PVC, poly(vinyl chloride), roofing membranes, shattering, T_g, thermal analysis, unreinforced PVC.

INTRODUCTION

The performance of many PVC roof membrane systems has been quite good. Numerous problems, however, have been reported with several of the early generation unreinforced (also referred to as "non-reinforced") PVC membranes. The Midwest Roofing Contractors Association (MRCA) in 1979 and 1982,[1,2] Griffin in 1982,[3] Wallace in 1983,[4] and Rosenfield in 1984,[5] reported shrinkage, embrittlement, "impact fractures" and other unidentified types of problems. The majority of these problem jobs utilized unreinforced membranes, although in some instances, there were reports of reinforced PVC membranes experiencing embrittlement and/or splitting problems.

As early problems began to appear, many people believed that a thicker membrane was needed, since most of these early jobs had membranes that were approximately 0.81mm or 0.86mm (32 or 34 mils) thick. A re-evaluation of the sheet's formulation was also suggested by some. However, Rosenfield recommended that PVC membranes be "restricted" to reinforced sheets. Corps of Engineers Guide Specification 07555 on PVC membranes was subsequently developed. It prohibited the use of unreinforced PVC membranes on U.S. Army facilities.[6]

In these early problem reports it is unclear if the problem phenomenon referred to as "shattering" was experienced. Shattering is "characterized by a generalized non-linear fragmentation of the membrane. Each fragment may be a few hundred square feet in total area. Typically, when a shatter occurs, it extends throughout the entire roof area, from one edge or perimeter to the other, and is judged to be non-repairable."[7]

Shattering typically has the potential to be quite devastating, since the building can suddenly become vulnerable to water infiltration throughout virtually the entire roof area. Dupuis described this type of roof problem as a "failure level IV."[8] A level IV failure is "abrupt, total, and in most instances without warning." (See Figures 1 to 4.)

In early 1990, the National Roofing Contractors Association (NRCA) became aware of an increased number of shatter reports. NRCA staff followed-up by analyzing Project Pinpoint (a data base of problem jobs, as described in Reference 9). The first incidence of shattering was reported to Project Pinpoint in 1983. A marked increase in the number of reports in 1988 and 1989 were recorded in the data base. A summary of the Project Pinpoint data on shattering is presented in Appendix 1.

Although the total number of Project Pinpoint shatter reports was small, considering the market share of PVC membranes and the nature of the problem, NRCA decided to contact all of the manufacturers of PVC membranes to solicit their input on this phenomenon. Based upon that input, NRCA surveyed its contractor membership in the spring of 1990. A summary of the survey responses is presented in Appendix 2. The survey identified shattered membranes by six manufacturers, four of which in 1990 no longer manufactured PVC roof membranes in the U.S.

Subsequent to the survey, NRCA continued to compile information on reports of shattering, although there were no additional surveys. A summary of these additional reports is presented in Appendix 3.

As can be seen in Appendices 1 to 3, the vast majority of the shatters reported to NRCA involved ballasted membranes that were several years old. Also, while many of the membranes were ~0.86mm (32 or 34 mils) thick, a high percentage of the membranes were 1.22mm (48 mils) or thicker. Membranes have shattered on both small and large roofs (from less than $90m^2$ [10 squares] to over $9,000m^2$ [1,000 squares]). And while the majority of the shatters have occurred on low-slope roofs, some have also occurred on slopes up to 4:12. The Project Pinpoint data, survey data and subsequent reports to NRCA are all highly correlated. It is also important to note that of the approximately 255 shatter reports received by NRCA, all have involved unreinforced membranes.

In the summer of 1990, the Single Ply Roofing Institute (SPRI) and NRCA began work on a joint document regarding shattering. The document, which was completed in September of that year, described the shattering phenomenon, discussed membrane identification and early warning signs, and presented information on maintenance and cold weather precautions.[7] SPRI also formed a task force to address this subject.[10]

In 1991, NRCA and the Institute for Research in Construction, of the National Research Council of Canada, began a cooperative research program on PVC shattering. The purpose of the research, is to further understand the shattering phenomenon, develop a technique that can be used to assess the shatter potential of existing unreinforced membranes, and develop additional criteria for incorporation into ASTM D 4434 (the standard for PVC roofing sheets).[11] This paper is a progress report on the work accomplished to date.

PROBLEM CAUSES

The cause or causes of shattering are not precisely understood. However, it is believed that shattering is related to a change in the physical properties of the membrane which, when combined with cold temperatures, results in the development of large tensile stresses in the membrane.

Membrane tensile stresses can be induced by membrane shrinkage due to plasticizer migration or formation of new chemical bonds. Stresses can also be induced by low temperature, as reported by Dupuis in 1983.[12] In addition to inducing stress, low temperatures may cause the membrane to become rigid (brittle).

If an unreinforced membrane accumulates enough tensile stress, it may rupture. The rupture may be spontaneous or it may occur by someone walking on the roof or by some object falling on the roof. Upon rupture, the membrane usually lacks sufficient strength to prevent propagation of the split. As the split propagates, it branches into multiple lines of rupture, as can be seen in Figures 1 to 3.

Information gathered to date indicates that only a relatively small number of unreinforced membranes have shattered. However, since most of the manufacturers of these products are no longer in business, it is difficult to determine the number of roofs installed with this product. Also, data are not available on the number of shatters reported (or attempted to be reported) to these manufacturers. The number of potential shattered jobs has also been reduced to some extent by building owners replacing roofs.

The following sections describe how and why the physical properties of a membrane may change. Through the utilization of thermal analysis, the membrane's glass transition temperature (the point at which the membrane becomes brittle) can be determined. The glass transition temperature appears to play an important role in shattering.

UTILIZATION OF THERMAL ANALYSIS

The application of thermoanalytical techniques in the characterization of roofing membranes is currently being studied by the CIB/RILEM joint committee on roofing.[13] Approximately a dozen papers have been written regarding thermal analysis and roofing membrane characterization.[14-26] Thermal analysis is a technique that can provide some insight as to why some roofing materials fail more prematurely than others. Dynamic mechanical analysis (DMA or DMTA) can be used routinely to determine various properties of a roofing membrane, e.g., the glass transition temperature. DMA instruments usually employ forced vibration conditions to deform a sample and study its viscoelastic response. Since the instruments have the capability of not only varying the applied frequency but also the temperature, DMA falls under the broad terminology of thermal analysis. Polymeric roofing membranes are evaluated using various test methods developed for the assessment of durability. Mechanical properties of polymeric materials have two facets; one is related to the macroscopic behavior and the other, to the molecular behavior which includes chemical composition and physical structure. For engineering applications the description of mechanical behavior under the design conditions is generally all that is required. Accordingly, the information obtained from these tests does not explain why a material has failed and how it can be improved, unless the failure is related to structural strength. If the failure is related to molecular activity, additional information is necessary to comprehend the problem fully.

In the work reported here, the glass transition temperature of unreinforced PVC roofing membranes which had shattered was obtained by dynamic mechanical thermal analysis. These values were then compared with the appropriate (i.e., same manufacturer, product and thickness) PVC sample stored in the NRCA archives ("control samples"). A brief description of T_g and DMA are given here. A more detailed description can be found in Reference 13.

The glass transition temperature (T_g) is a property of a polymer and is defined as the temperature at which the polymer loses flexibility and becomes brittle.[27-32] This is a reversible process and the polymer will regain flexibility above the T_g. The glass transition temperature is affected by free volume, attractive forces between molecules, rotation about molecular bonds, stiffness of molecular chain and length of molecular chain. Plasticizers can help in reducing the T_g by interfering with the chain motions and thereby softening the polymer. It is also important to note that the glass transition temperature is always below the melting temperature of the polymer. Generally, the tensile strength of polymeric materials below the glass transition temperature is superior to the strength above T_g. However, this is not necessarily a positive attribute.

The glass transition temperature of a polymer can change with aging of the material (e.g., weathering). The glass transition temperature may be increased due to thermal degradation of PVC or loss of plasticizer. The thermal degradation is manifested through changes in color (usually darkening) of the membrane, and deterioration of chemical and physical properties. The heat degradation of PVC is attributed to the dehydrochlorination of the polymer (evolution of HCl gas). In some PVC membranes this can occur at temperatures as low as 100°C (212°F).[18,22] Photochemical degradation (i.e., ultraviolet radiation) shows similar characteristics as those described in thermal degradation. The main difference is that the changes might not be visually observed (e.g., no color change might be noted). Moreover, the processes causing thermal degradation are understood better than those causing photochemical degradation.

Description of DMA

Three terms can be derived from the stress-strain relationship as measured by DMA. The first term is the *storage* modulus (E') and is a measure of recoverable strain energy in a deformed body (i.e., it is related to stiffness). The second term is the *loss* modulus (E") and is associated with the loss of energy as heat due to the deformation of the material. The third term is the ratio of E"/E' which yields the loss tangent or damping factor (tanδ). A more detailed description of DMA can be obtained in References 17 and 33-37.

A typical DMA plot containing E', E" and tanδ, as a function of temperature, is shown in Figure 5. If more than one peak is observed in a given E" or tanδ curve, then the peak closest to the melting point or degradation point is usually labelled as the α-peak. The β-peak is the peak immediately below the α-peak. The T_g due to the main backbone of the polymer can normally be obtained from the most intense peak observed in either the E" or tanδ curves. Often, this intense peak corresponds to the α-transition. This can be verified by a DMA experiment at various frequencies. It should be noted that the T_g obtained by E" and tanδ will be different. ASTM recommends using the peak in the E" curve.

The glass transition temperature, determined by DMA, is dependent on the heating rate and frequency. Therefore, T_g values obtained by this dynamic technique are generally different from that obtained by static techniques (with respect to frequency) such as differential scanning calorimetry (DSC). Moreover, the temperature of a polymer can also be increased by subjecting the material to high frequency and high amplitude oscillations. Thus, when studying dynamic mechanical properties, low frequencies and low strain amplitudes should be used. Low strain amplitude is associated with the linear region of a stress-strain curve, but if a large stress or strain amplitude is applied to a viscoelastic material, high internal heat due to molecular vibration is generated. This results in a nonlinear viscoelastic response that is quite complex to analyze. Also, in nonlinear viscoelastic regions, the material is permanently modified. For example, microscopic crack formation or failure due to fatigue can result.

Clamping will affect modulus results and therefore absolute modulus values are obtained with great difficulty using DMA. If care is taken, results within a given laboratory will be reproducible, hence comparison amongst various materials is feasible. Although DMA is weak with respect to the accuracy of absolute modulus, the transition temperatures can routinely be determined with great accuracy. The method used to obtain T_g (i.e., E" or tanδ peak temperature) affects the value and, therefore, the parameter must be specified. As long as the same parameter is used throughout a study, the trend observed will be the same regardless of the parameter used.

EXPERIMENTAL

All PVC membrane samples obtained from shattered roofs were unreinforced. Wherever possible, a sample was taken from an area that was unexposed (the bottom portion of an "unbonded flap" at a seam (see Figure 6)), as well as from the exposed shattered area. Moreover, samples from the NRCA archives (i.e., unexposed and unweathered) were included in this study. A typical composition for a generic unreinforced PVC membrane is shown in Table 1.

Dynamic Mechanical Analysis (DMA)

The glass transition temperature of the membranes was obtained using a Rheometrics RSA II (software version 3.0.1) dynamic mechanical analyzer equipped with a mechanical cooling device. The following experimental profile was used for this study:

Geometry:	Dual cantilever
Sample width:	3.75-6.0mm
Sample thickness:	0.7-1.3mm
Sample length:	36.67mm
Sweep type:	Time/cure
Frequency:	1 Hz (6.28 rad./sec.)
Temperature range:	-70°C to +30°C
Heating rate:	2.0°C/min.
Time per measurement:	1.0 min.
Strain:	1×10^{-3} to 2×10^{-3}
Delay before test:	1.0 sec.
Correlation delay:	1.0 sec.
Auto tension:	No
Auto strain:	No

The glass transition temperature was obtained from the average of at least two and no more than four specimens from the same sample. The values are reported as the maximum in the loss modulus (E") vs. temperature curve. It is also possible to use the maximum of the tanδ peak vs. temperature curve, however, it was found that the E" curve gave a better correlation with traditional mechanical data (e.g., tensile and elongation).[19,22] The glass transition temperatures of the various samples are summarized in Tables 2-5.

VISUAL OBSERVATIONS

When examined under 8x magnification, weather-induced checking on the exposed side of the samples from mechanically attached membranes could be easily seen. It appeared that the checking depth was minor. On sample 90/91-20 (10 years old, from California), pronounced surface checking was visible with the naked eye. Surface checking was also visible on 90/91-23 (7.5 years old, from Michigan). (See Figure 7.) Under 8x magnification, the width of the check lines on this sample was greater than that observed on samples from other mechanically attached jobs. All of the mechanically attached samples included in this study were of the same manufacturer, except for 90/91-23. Samples from ballasted membranes were examined under 8x magnification, but checking was not observed.

On some of the samples from ballasted and mechanically attached samples, scratches could be seen in the top side of the membrane. These appeared to be caused during or after membrane application. Some of them may have been caused during membrane removal, however, others appeared to be old scratches. The role (if any), in terms of stress concentration, that scratches play in the shattering phenomenon is unknown.

On some of the samples from 90/91-2 (10 years old, ballasted, Virginia), an "orange peel" surface was visible on the top side of the sheet. This only occurred on samples that were fairly clean. Other samples from this job had a good deal of dirt on the membrane. These samples exhibited a smooth surface after the dirt was removed. (See Figure 8.)

After cleaning off the dirt, one of the samples from 90/91-13 (10 years old, ballasted, Colorado) also exhibited an orange peel surface, but it was not as pronounced as on the samples from 90/91-2. All of the samples from 90/91-13 were quite dirty. The sample that had the orange peel also had a discolored mottled pattern. The discolored areas were light purple. Similar discolorations were observed on some of the samples from other jobs.

Several samples, or portions of samples were noticeably embrittled. For those samples with an unbonded flap, typically the unexposed flap was supple, whereas the exposed portion of the membrane was often relatively stiff.

RESULTS AND DISCUSSION

Table 2 contains T_g data for the control samples obtained from the NRCA archives. As can be seen, the glass transition temperature for samples C-1A through C-9A ranges from -23°C to -50°C. The shattered samples listed in Table 3 are those that shattered in 1988/89 and 1989/90. In nearly all the cases, the T_g shifted to much higher temperatures. It is interesting that for shattered samples not exposed to the environment (e.g., 88/89-2.1A bottom and 88/89-2.3A bottom) the ΔT_g was negligible (see Figure 9). Hence, it would appear that only factors related to outside exposure to the environment are affecting the samples. Some of these factors include contact with mud, micro-organisms, oxygen, temperature, and ultraviolet radiation (depending upon degree of ballast shielding).[38] It is also possible that dirt in the ballast and/or fungus attack might be extracting some of the plasticizer present in the membrane. Apart from samples 88/89-2.4A and 89/90-1, the T_g was between 8°C and 17°C higher than when it was originally installed. If the cause of the change in T_g is due to plasticizer migration or formation of new chemical bonds, then it is possible that the unreinforced material is shrinking and/or that the coefficient of thermal expansion is changing, thus generates an induced load. Moreover, the technique used in the manufacturing process may also be a factor in dimensional stability. Some manufacturing processes are more likely than others to build-in stress.

The glass transition temperatures of the samples from roofs that shattered in 1990/91 are tabulated in Table 4. As was seen for the previous series, ΔT_g varied quite extensively. The T_g of some samples shifted to a higher temperature by as much as 36°C when compared to the control. Once again, samples taken from an unbonded flap yielded a T_g similar to that of the control. The only exceptions are those belonging to the 90/91-10 series. In this case, the bottom unbonded flap sample was -41°C while the control (C-9A) was -23°C. It is possible that the control sample is not for this series of samples. This could have occurred if the formulations had been modified between the production of control and the actual roof membrane. If it is assumed that the control should have been in the vicinity of -41°C, then the ΔT_g for this series ranges from 20°C to 43°C. Moreover, it is interesting to observe how, for a given roof sample, the T_g varies as sample is tested as one gets further away from the shatter line. For example, sample 90/91-10.1A , area #1 and area #2 have a T_g of approximately -21°C, while area #3 (near the shatter line) has a T_g of only -7°C.

The data for the 91/92 series follows the same trend as the other series (see Table 5). In some cases, the T_g was shifted to 19°C higher for the shattered sample than for the corresponding control. The only exception was for sample 91/92-1A. In this case, the control sample is C-9A and as previously mentioned might be the wrong control.

Generally, it would appear that the glass transition temperature as well as the ΔT_g may be useful in explaining why a roof shattered. The T_g, however, cannot explain all the causes of shattering, and other factors may be involved. For example, samples 88/89-2.4A and 89/90-1 both have T_g less than -30°C and a ΔT_g of only +2 and +3 (see Table 3). In these cases, it is possible that on the day the roofs shattered the temperature was below -30°C. To verify this hypothesis, meteorological data is required. The findings of this comparison will be published in the near future.

All of the above discussion applies to unreinforced PVC membranes. This type of roofing membrane has almost exclusively been replaced by reinforced PVC membranes which exhibit superior dimensional stability. Therefore, it is important to verify if the glass transition temperature can still be applied in predicting the behavior of these reinforced membranes. Paroli and Dutt have recently published their findings on the application of DMA in ranking the thermal stability of reinforced PVC membranes.[22] In this study PVC samples were heat aged in an oven and then characterized by DMA. The results are summarized in Table 6. As can be seen, the T_g for samples V1 and V3 changed significantly as the samples were aged. The glass transition temperature for sample V2 only changed when the sample was subjected to aging at 130°C for at least seven days. It was concluded from this study that sample V1 was the least heat-resistant PVC membrane. It is important to note that this was also observed in the field, i.e., roofs with membrane V1 had more problems than with V2 or V3. Therefore, even though PVC membranes are now reinforced, the T_g of these membranes should still be verified and monitored to predict relative stability. It appears that formulation of the PVC membrane is critical to the long-term performance.

CONCLUSIONS

Glass transition temperature may be useful in explaining the shattering of unreinforced roofing membranes. T_g can also be used to predict the behavior of reinforced roofing membranes.

Dynamic mechanical analysis is a valuable tool in characterizing reinforced and unreinforced PVC roofing membranes.

More research is required to correlate the mechanical properties of the shattered samples with the glass transition temperature. Also, correlation with meteorological data is required. Research also should include samples from older roofs that have not shattered.

RECOMMENDATIONS

To reduce the possibility of shattering existing unreinforced PVC membranes:

- Avoid rooftop traffic when the ambient temperature is below approximately +8°C (+50°F), or consult the membrane manufacturer for a recommendation regarding minimum temperature.[7] *(Note: A relatively high temperature is recommended due to limited temperate data at time of shattering. Also, the membrane temperature may be substantially below the ambient temperature).*
- It is recommended the building owner have the roof inspected semiannually by a roofing professional knowledgeable of PVC membranes. In particular, the inspector should look for potential early warning signs of shattering, such as wood nailers, base flashings or metal flashings that have pulled away from their initial position (see Figure 10). Also, look for plumbing vents or other penetrations that have been displaced (see Figure 11). A membrane under high stress may appear to be visibly taut. Another potential early warning sign is an embrittled membrane (i.e., the membrane has lost flexibility).
- During the inspection, if items are found that could either puncture the membrane (e.g., protrusions at flashings) or fall onto the roof (e.g., tree limbs), corrective action is recommended, as these items may initiate shattering.

  Although these potential early warning signs do not necessarily indicate the roof will shatter, it is recommended that they not be ignored if found.
- If potential early warning signs are observed, membrane replacement or repair work is recommended.

  As a repair to relieve membrane stress, new membrane material may be added around the building perimeter and at penetrations (if needed) as Carlson described in 1991.[39] However, the repair may or may not be successful in greatly extending the roof's service life. The shattered roof in Figure 1 reportedly had relief strips added at the perimeter a year or two before the job shattered. Prior to executing repairs or maintenance to relieve stress or for other reasons, it is recommended the manufacturer of the membrane be contacted for recommendations. If the manufacturer is no longer in business, refer to Carlson's articles.[39]

  In evaluating repair versus replacement, there are several issues to consider. Chief among these are the contents or occupancy of the building. If a shatter and subsequent water infiltration would be extremely detrimental (either in the cost of damaged goods or to business interruption), then replacement may be prudent, since the consequences of implementing a repair (which may fail) would be severe. Moreover, in considering repair versus replacement, lab analysis of samples from the roof in question may provide useful data (see "Laboratory evaluation of shatter potential" below).

  It is recommended the slip sheet underlayment also be evaluated when considering repair versus replacement. For a time, unsaturated asbestos felt was sometimes used as the slip sheet. If such a sheet was utilized, the difficulties of dealing with a shattered job could be greatly compounded by the asbestos-containing slip sheet. Because the felt was not saturated with asphalt, it could be friable. Accordingly, if the roof is exhibiting potential early warning signs of shattering and if it has an unsaturated asbestos felt slip sheet, roof replacement under controlled conditions may be a prudent decision by the building owner.
- If an unreinforced membrane is to be recovered, special precautions are recommended.[40] If the membrane is to be left in place, it is recommended that it be cut at the perimeter and around penetrations. And in the field of the roof, cut into pieces approximately 3m x 3m (10 ft. x 10 ft.).

It is recommended that work be performed in temperatures greater than approximately +8°C (+50°F), to avoid shattering during the reroofing work and thus avoid potential interior water damage. If work is conducted below +8 °C (+50 °F), special cold weather precautions are recommended. These include warming the membrane prior to cutting and having a contingency plan in place to deal with a shatter if it occurs. Also, night tie-ins may be problematic, since the existing membrane may shrink after the tie-in is made.

Laboratory evaluation of shatter potential

It appears that some insights into a membrane's shatter potential may be achieved by performing thermal analysis on several samples taken from the roof. As part of the T_g analysis, it would be important to find and analyze at least one unbonded flap, since it appears to represent the membrane in an aged, but unexposed condition.

In addition to T_g work, it may be helpful to also perform temperature-induced load tests on samples from the roof, as described by Dupuis.[12]

If an existing unreinforced membrane is exhibiting potential early warning signs of shattering, laboratory evaluation may be useful. While there is time and expense involved in testing, if the roof is large enough, this evaluation may indeed be worthwhile. If the analysis indicates that the T_g has changed significantly, then it should be realized that the original properties of the membrane have changed. This information could then be utilized in conjunction with field and other laboratory investigations to determine what remedial or replacement work would be appropriate.

ASTM D 4434

As currently drafted, the next edition of ASTM D 4434 will only include reinforced membranes. However, the standard should also include criteria and test methods regarding the relative stability of the glass transition temperature. As can be seen in Table 6, the T_g stability of three different reinforced products varied significantly.

In addition, ASTM D 4434 needs to be strengthened to differentiate between those reinforced PVC sheets that offer a long service life and those that do not. For example,

Figure 12 is of a reinforced PVC membrane that has cracked completely through the sheet (however, the reinforcement is still intact). While repairable, this condition does allow water infiltration. And if this type of problem occurs extensively, repair is problematic.

The accelerated weathering test procedure introduced by Lys in 1985 should be considered.[41]

PVC MEMBRANES TODAY

Essentially all PVC roof membranes supplied to the U.S. market are now reinforced. At this time, it appears unlikely that these products will experience shattering. In addition to the utilization of reinforcement, PVC membranes are typically much thicker than the early generation products. The increased thickness typically results in a greater reservoir of plasticizer, which should result in a longer membrane service life.[38] However, simply having a thicker reinforced sheet does not necessarily ensure good long-term performance, as other factors (such as amount and quality of plasticizer, formulation and manufacturing process) influence performance.

Reinforced PVC roof membrane systems can be expected to perform quite well when quality products are installed by professional roofing contractors in well-designed systems. Many reinforced PVC roof membranes have successfully performed for 30 years in Europe and nearly 20 years in the U.S. and Canada. If the next edition of ASTM D 4434 is similar to the present draft, this should be a greatly improved standard for reinforced PVC roof sheets, which will allow specifying these types of products with greater confidence in their performance.

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APPENDICES

Appendix 1
Summary of Project Pinpoint Analysis, Prepared in Early 1990

1. The data base contained 22 shattered jobs. During follow-up telephone conversations to verify and obtain additional data, four additional shattered jobs were reported. The following summary includes all 26 jobs.
2. Seventy-seven percent of the jobs were unreinforced. For the remaining jobs, it was unknown whether the sheets were reinforced. Based upon subsequent reports (Appendices 2 and 3), it is probable that these unknown sheets were also unreinforced.
3. Seventy percent of the shatters occurred in 1988-1990. Four percent of the shatters occurred prior to 1985. The earliest shatter occurred in 1983.
4. The median roof age at time of failure was 7.5 years. The roof age at time of failure ranged from three to 11 years. The age was unknown on 15 percent of the jobs.
5. Membrane Attachment:
   ballasted:...85%
   mechanically attached:.........................8%
   fully adhered:.......................................4%
   unknown:..4%
6. Nominal membrane thickness (at time of manufacture):
   0.81mm or 0.86mm (32 or 34 mils):......27%
   1.22mm (48 mils):..................................42%
   1.52mm (60 mils):....................................4%
   other/unknown:......................................27%
7. The shatters occurred in 14 states, including a few of the Southern states.

Appendix 2
Summary of 1990 NRCA Survey on PVC Shattering

1. Eighty-four contractors reported 186 shatter jobs.
2. All 186 jobs utilized unreinforced membranes.
3. Seventy-seven percent of the shatters occurred in 1988-1990. Three percent of the shatters occurred prior to 1985. The earliest shatter occurred in 1978.
4. The median roof age at time of failure was 8.5 years. The roof age at time of failure ranged from three to 13 years. The age was unknown on six percent of the jobs.
5. Membrane Attachment:
   ballasted:...91%
   mechanically attached:.............................6%
   fully adhered:..3%
6. Nominal membrane thickness (at time of manufacture):
   0.81mm or 0.86mm (32 or 34 mils):......47%
   1.22mm (48 mils):..................................39%
   1.52mm (60 mils):....................................3%
   other/unknown:......................................11%
7. Someone was on roof at time of shatter:
   yes:..22%
   no:...67%
   unknown:...11%
8. Significant temperature drop prior to shatter:
   yes:..53%
   no:...28%
   unknown:...19%
9. Ambient temperature at time of shatter:
   above 0°C (32°F):....................................12%
   below 0°C (32°F):....................................49%
   unknown:...39%
10. The shatters occurred in 30 states, including several of the Southern states.
11. The manufacturer was identified for 72 percent of the jobs. These jobs utilized six manufacturers. At the time of the survey, four of the six manufacturers reportedly no longer manufactured PVC roof membranes in the U.S.

Note: The survey data were not verified by NRCA.

Appendix 3
Summary of Shatter Reports to NRCA, Subsequent to 1990 Survey

1. Twenty-two shattered jobs were reported during the 1990/1991 winter. Seven shattered jobs were reported

during 1991/1992. All 29 jobs utilized unreinforced membranes.

2. The median age at time of failure was 10.5 years. The roof age at time of failure ranged from six to 14 years. The age was unknown on 28 percent of the jobs.
3. Membrane Attachment:
   ballasted: 59%
   mechanically attached:............................21%
   not reported: 21%
4. Nominal membrane thickness (at time of manufacture):
   0.81mm or 0.86mm (32 or 34 mils):.......21%
   1.22mm (48 mils):...................................34%
   1.52mm (60 mils):...................................10%
   other/unknown:.......................................34%
5. The shatters occurred in 14 states, including the San Francisco Bay area of California.
6. Following the 1990 survey, 11 shattered jobs were reported, which occurred in 1988, 1989 or 1990. These had not been reported in the survey or in Project Pinpoint. Seven of these jobs were ballasted. Four were mechanically attached.
7. Three shatters were reported during the winter of 1992/1993 (through February 1993). All three jobs were mechanically attached. Two were 1.52mm (60 mils) and one was 1.22mm (48 mils) nominal thickness at time of manufacture. One job was 9 years old and one was 10 years old. The age of the other job was unknown.

Appendix 4
Description of Jobs From Which Samples Were Obtained

Note: Age at time of shatter is approximate. Thickness is the probable nominal thickness at time of manufacture.

88/89-1: Ballasted, 8 years old, 1.22mm (48 mils), over foil-faced polyisocyanurate, Iowa.

88/89-2: Ballasted, 11 years old, 1.22mm (48 mils), over a kraft paper slip sheet over polyurethane, Indiana.

89/90-1: Mechanically attached, 9.5 years old, 1.52mm (60 mils), over a smooth surface built-up membrane, Pennsylvania.

90/91-2: Ballasted, 10 years old, 1.22mm (48 mils), over kraft paper slip sheet over rigid fiberglass/polyurethane composite board, Virginia.

90/91-3: Ballasted, age unknown, unknown thickness, substrate not identified, Illinois.

90/91-5: Ballasted, 6 years old, 0.86mm (34 mils), over kraft paper slip sheet over polystyrene, Virginia.

90/91-7: Ballasted, 8 years old, 0.86mm (34 mils), over kraft paper slip sheet over polystyrene, Virginia.

90/91-10: Ballasted, 7.5 years old, 0.86mm (34 mils), over polyester slip sheet over perlite, Illinois.

90/91-13: Ballasted, 10 years old, 1.22mm (48 mils), over kraft slip sheet over polystyrene, Colorado. Temperature at time of shatter was reported to be -28°C (-19°F). Someone was on the roof at time of shatter.

90/91-14: Mechanically attached, 8 years old, 1.52mm (60 mils), over kraft paper over expanded polystyrene, Illinois. Temperature at time of shatter was reported to be around -7°C (+20°F).

90/91-16: Mechanically attached, 14 years old, 1.52mm (60 mils), over slip sheet over expanded polystyrene, Pennsylvania. Temperature at time of shatter was reported to be around -15°C (+5°F).

90/91-20: Mechanically attached, 10 years old, 1.52mm (60 mils), over kraft paper over expanded polystyrene, California.

90/91-23: Mechanically attached, 7.5 years, unknown nominal thickness at time of manufacture, over insulation (type not reported), Michigan. Roof slope was approximately 4:12.

91/92-1: Ballasted, 12 years old, 0.86mm (34 mils), over fabric scrim slip sheet over lightweight insulating concrete, Illinois.

91/92-2: Ballasted, 13 years old, 1.22mm (48 mils), over kraft paper over expanded polystyrene, Colorado. Temperature at time of shatter was reported to be around -7°C (+20°F).

91/92-3: Ballasted, 11 years old, 1.22mm (48 mils), substrate not identified, Indiana.

91/92-5: Ballasted, 11 years old, 1.22mm (48 mils), substrate not identified, Maine.

91/92-7: Ballasted, 7.5 years old, 1.22mm (48 mils), over expanded polystyrene (a separator sheet was not reported), Iowa. Temperature at time of shatter was reported to be around -12°C (+11°F), or a few degrees warmer.

Ingredients	% by Weight (Approx.)	Function
PVC Resin	50 - 55	Basic material (powder or granular)
Plasticizers	25 - 30	Impart flexibility
Fillers	5 - 10	Increase dimensional stability, and reduce cost
Pigments	0.5 - 1.0	Provide color and UV stability to the PVC compound
Processing oils and biocides	0.5 - 1.0	Improve processing and resistance to biological attack
Stabilizers	2 - 3	Provide resistance to heat and light during manufacture and after installation
TOTAL	100	

***Table 1** Typical composition of a generic unreinforced PVC roofing membrane.*

Sample	Average T_g (°F)	Average T_g (°C)	Specified Thickness (mils)	Sample Thickness (mils)	Approximate Year of Manufacture	Intended System Design	Manufacturer
C-1A	-31	-35	48	48-49	1984-85	Ballasted	A
C-2A	-29	-34	48	48	1979	Ballasted	A
C-3A	-38	-39	60	59	1979	Mechanically Attached	A
C-4A	-56	-49	32	31	1978	Ballasted	D
C-5A	-58	-50	45	43	1978	Ballasted	D
C-6A	-22	-30	48	47-51	1985	Ballasted	C
C-7A	-45	-43	34	32	1979	Ballasted	E
C-8A	-33	-36	45	44	1979	Ballasted	E
C-9A	-9	-23	34	33	1974-75	Ballasted	B
Note: Samples from shattered jobs that correlate to control samples C-4A, C-5A, C-6A and C-8A were not obtained. 1 mil = 0.0254 mm							

Table 2 Glass transition temperatures of unreinforced PVC membranes from NRCA archives ("control samples").

	T_g Sample		T_g Control		ΔT_g		Corresponding Control Sample	Sample Thickness	Probable Nominal Thickness
Sample	(°F)	(°C)	(°F)	(°C)	(°F)	(°C)		(mils)	(mils)
88/89-1.1	-8	-22	-29	-34	+21	+12	C-2A	42	48
88/89-1.2	-11	-24	-29	-34	+19	+10		45-46	
88/89-1.3	0	-18	-29	-34	+29	+16		41-43	
88/89-1.4	-6	-21	-29	-34	+23	+13		43-44	
88/89-2.1A (top)	-4	-20	-29	-34	+25	+14	C-2A	39-40	48
88/89-2.1A (bottom)	-33	-36	-29	-34	-4	-2		46-47	
88/89-2.1C	-4	-20	-29	-34	+25	+14		39	
88/89-2.2A	-17	-27	-29	-34	+12	+7		41-43	
88/89-2.3A (top)	-13	-25	-29	-34	+16	+9		39-42	
88/89-2.3A (bottom)	-33	-36	-29	-34	-4	-2		45-46	
88/89-2.4A	-26	-32	-29	-34	+3	+2		39-43	
88/89-2.5A	-9	-23	-29	-34	+20	+11		40-42	
89/90-1	-33	-36	-38	-39	+5	+3	C-3A	52	60

$\Delta T_g = T_g$ (shattered sample)-T_g (control). 1 mil = 0.0254mm

Note: 1. Key to sample identification (e.g., 88/89-2.1C):

- 88/89 = Year of shatter, winter of 1988/89
- -2 = chronological order of shatter reports to NRCA (in this case, this was the second job reported in 1988/89).
- .1 = chronological order of samples from job number 2.
- .C = this sample was taken from a larger specimen.
- 88/89-2.1A (top) = specimen taken from a sample with an "unbonded flap." "Top" indicates that the specimen is from the exposed membrane.
- 88/89-2.1A (bottom) = specimen taken from a sample with an "unbonded flap." "Bottom" indicates that the specimen is from the unexposed bottom flap area.

2. Jobs 88/89-1 and 88/89-2 were ballasted.
Job 89/90-1 was mechanically attached.
See Appendix 4 for further detail.

Table 3 Glass transition temperatures of shattered unreinforced PVC membranes (88/89 and 89/90 series).

	T_g Sample		T_g Control		ΔT_g		Corresponding Control Sample	Sample Thickness	Probable Nominal Thickness
Sample	(°F)	(°C)	(°F)	(°C)	(°F)	(°C)		(mils)	(mils)
90/91-2.1A	+3	-16	-29	-34	+32	+18		35-37	
90/91-2.3A	-4	-20	-29	-34	+25	+14		36-37	
90/91-2.5	-9	-23	-29	-34	+20	+11		36-37	
90/91-2.6A	-6	-21	-29	-34	+23	+13	C-2A	36-37	48
90/91-2.7A	+9	-13	-29	-34	+38	+21		36-38	
90/91-2.10A	+5	-15	-29	-34	+34	+19		36-38	
90/91-2.18	+9	-13	-29	-34	+38	+21		37-39	
90/91-3.1A	+16	-9	NONE	NONE	—	—	NONE	35-38	UNKNOWN
90/91-5.1A	-33	-36	-45	-43	+13	+7	C-7A	28-30	34
90/91-7.1A	-19	-7	-45	-43	+65	+36	C-7A	28-31	34
90/91-10.1A Area #1	-6	-21	-9	-23	+4	+2		30-31	
90/91-10.1A Area #2	-8	-22	-9	-23	+2	+1		30-31	
90/91-10.1A Area #3	+19	-7	-9	-23	+29	+16		30-31	
90/91-10.1A (Bottom)	-42	-41	-9	-23	-32	-17		not measured	
90/91-10.2	+16	-9	-9	-23	+25	+14	C-9A	30-31	34
90/91-10.4 Area #1	+28	-2	-9	-23	+38	+21		30-31	
90/91-10.4 Area #2	+19	-7	-9	-23	+29	+16		30-31	
90/91-10.4 Area #3	+36	+2	-9	-23	+45	+25		30-31	
90/91-10.4 Area #4	+19	-7	-9	-23	+29	+16		30-31	
90/91-13.1A	-4	-20	-29	-34	+25	+14		39-43	
90/91-13.2A	-8	-22	-29	-34	+21	+12		41-43	
90/91-13.3A	-8	-22	-29	-34	+21	+12		35-40	
90/91-13.4A	-11	-24	-29	-34	+18	+10	C-2A	38-39	
90/91-13.4C	-9	-23	-29	-34	+20	+11		38-39	
90/91-13.5	+18	-8	-29	-34	+47	+26		37-38	
90/91-14.1 (Top)	-8	-22	-38	-39	+31	+17		52-53	
90/91-14.1 (Bottom)	-33	-36	-38	-39	+5	+3	C-3A	58	60
90/91-14.2A	+3	-16	-38	-39	+41	+23		50-51	
90/91-16.1A	-15	-26	-38	-39	+23	+13		50-52	
90/91-16.2A	-15	-26	-38	-39	+23	+13	C-3A	52-54	60
90/91-16.3	-13	-25	-38	-39	+25	+14		50-51	
90/91-20.1	+7	-14	-38	-39	+45	+25	C-3A	49-53	60
90/91-23.1A	+21	-6	—	—	—	—		44-45	
90/91-23.2 Area #1	+16	-9	—	—	—	—	NONE	45-49	UNKNOWN
90/91-23.2 Area #2	+16	-9	—	—	—	—		45-49	
90/91-23.2 Area #3	+21	-6	—	—	—	—		45-49	

$\Delta T_g = T_g$ (shattered sample)-T_g (control). 1 mil = 0.0254mm

Note: Jobs 90/91-14, 90/91-16, 90/91-20 and 90/91-23 were mechanically attached.
Other jobs were ballasted.
See Appendix 4 for further detail.
Area #1, #2, #3: Specimens from the same sample.

Table 4 *Glass transition temperatures of shattered unreinforced PVC membranes (90/91 series).*

	T_g Sample		T_g Control		ΔT_g		Corresponding Control Sample	Sample Thickness	Probable Nominal Thickness
Sample	(°F)	(°C)	(°F)	(°C)	(°F)	(°C)		(mils)	(mils)
91/92-1A	-44	-42	-9	-23	-35	-19	C-9A	29-30	34
91/92-2A (Top)	-18	-28	-29	-34	+11	+6		37-38	
91/92-2A (Bottom)	-31	-35	-29	-34	-2	-1	C-2A	44-45	48
91/92-3.1 (near shatter line)	+12	-11	-29	-34	+41	+23		41-43	
91/92-3.1 Area #2	-35	-37	-29	-34	-6	-3		41-43	
91/92-3.1 Area #3	-2	-19	-29	-34	+27	+15		41-43	
91/92-3.2 Area #4	+9	-13	-29	-34	+38	+18		41-43	
91/92-3.2 (near shatter line)	-22	-30	-29	-34	+7	+4		41-42	
91/92-3.2 Area #2	-24	-31	-29	-34	+5	+3	C-2A	41-42	48
91/92-3.2 Area #3	-18	-28	-29	-34	+11	+6		41-42	
91/92-3.2 Area #4	-26	-32	-29	-34	+3	+2		41-42	
91/92-3.3 (near shatter line)	+9	-13	-29	-34	+38	+21		41-42	
91/92-3.3 Area #2	+9	-13	-29	-34	+38	+21		41-42	
91/92-3.3 (Bottom)	-29	-34	-29	-34	0	0		48	
91/92-5.1 (near shatter line)	+28	-2	-29	-34	+57	+32		38-39	
91/92-5.1 (Bottom)	-9	-23	-29	-34	+20	+11	C-2A	44-45	48
91/92-7.1 (Top)	-4	-20	-29	-34	+25	+14		38-41	
91/92-7.1 (Bottom)	-33	-36	-29	-34	-4	-2	C-2A	44-45	48

$\Delta T_g = T_g$ (shattered sample)-T_g (control). 1 mil = 0.0254mm

Note: All of these jobs were ballasted.
See Appendix 4 for further detail.
Area #1, #2, #3: Specimens from the same sample.

Table 5 *Glass transition temperatures of shattered unreinforced PVC membranes (91/92 series).*

Heat-aging Schedule		T_g of Reinforced PVC Samples (°C)			ΔT_g (°C)		
Temp. (°C)	**Days**	**V1 (polyester reinforcement)**	**V2 (fiberglass reinforcement)**	**V3 (polyester reinforcement)**	**V1**	**V2**	**V3**
Control	—	-28	-33	-29	0	0	0
100	1	-27	-34	-25	-1	+1	-4
100	7	-26	-34	-27	-2	+1	-2
100	28	-16	-33	-20	-12	0	-9
130	1	-21	-34	-25	-7	+1	-4
130	7	-18	-23	-19	-10	-10	-10
130	28	-5	-25	-14	-23	-8	-15

Note: 1. $\Delta T_g = T_g$ (heat aged sample) -T_g (control).
2. Control = Unheated material
3. Sample thickness was between 1mm and 1.1mm

Table 6 *Glass transition temperatures of reinforced PVC membranes.*[22]

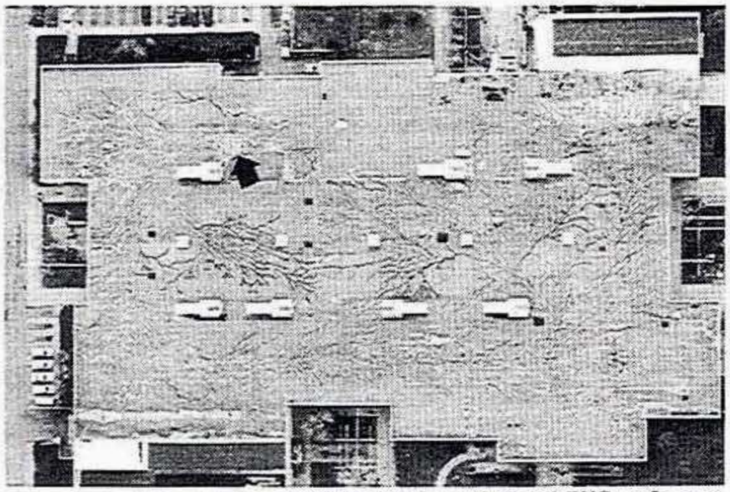

Photo credit: United Scanning Technologies

Figure 1 Aerial view of shattered ballasted unreinforced PVC roof system. Shatter initiated at the upper left, where indicated by the arrow. The shatter propagated in a counter-clockwise direction. One area at the top center portion of the roof did not initially shatter. However, it shattered a few days later. Membrane replacement is underway at the upper right and lower left corners.

Figure 2 General view of a shattered ballasted unreinforced PVC roof system.

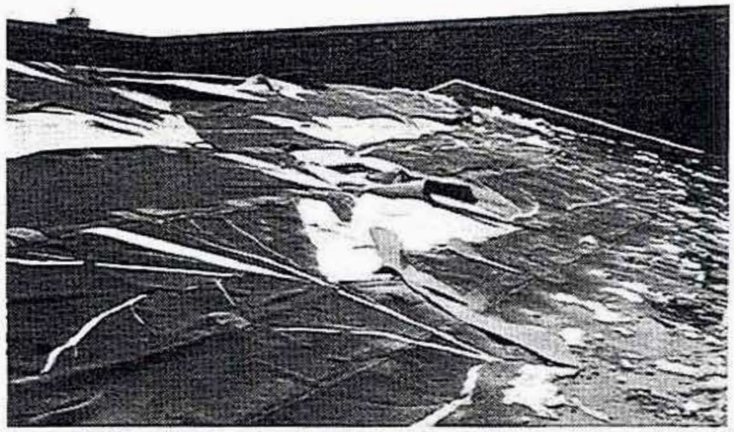

Figure 3 General view of a shattered mechanically attached unreinforced PVC roof system.

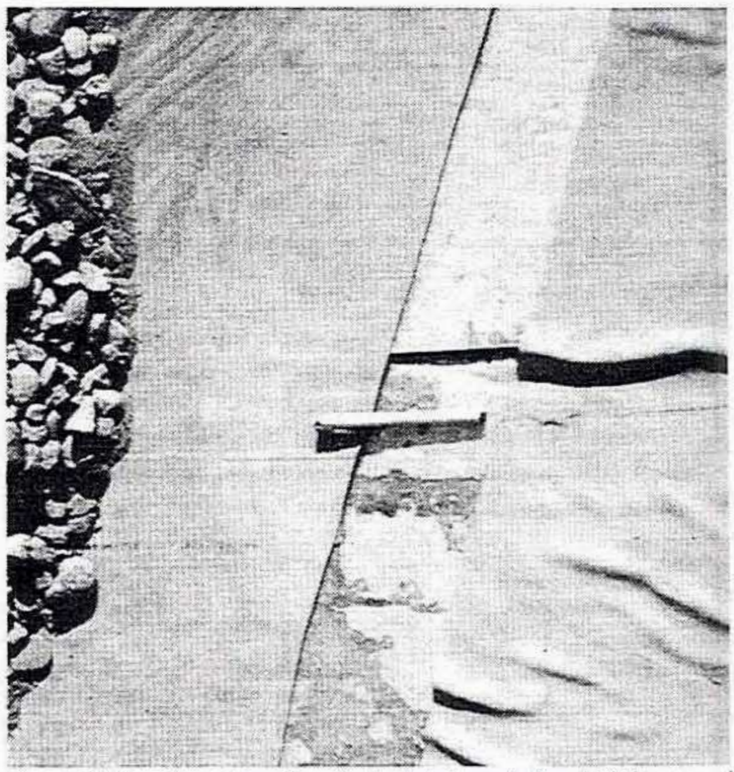

Figure 4 View of a rupture line of a ballasted unreinforced PVC system. A seam line occurs to the right of the ink pen. On the other side of the rupture line, the seam line is below the pen. Hence, the membrane moved left-right and top-bottom. At lines of rupture, the membrane is often open by several inches, as it is in this figure.

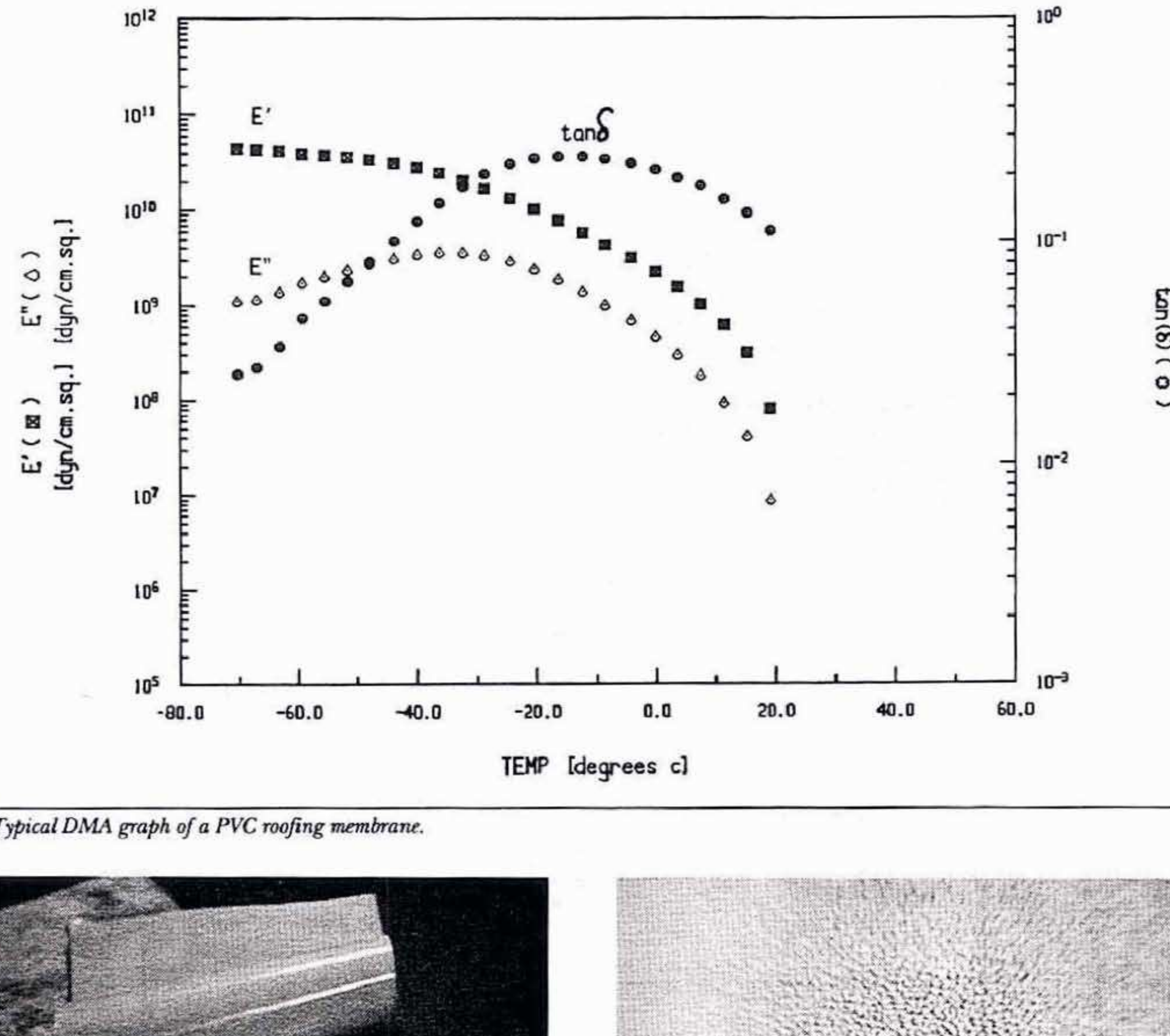

Figure 5 Typical DMA graph of a PVC roofing membrane.

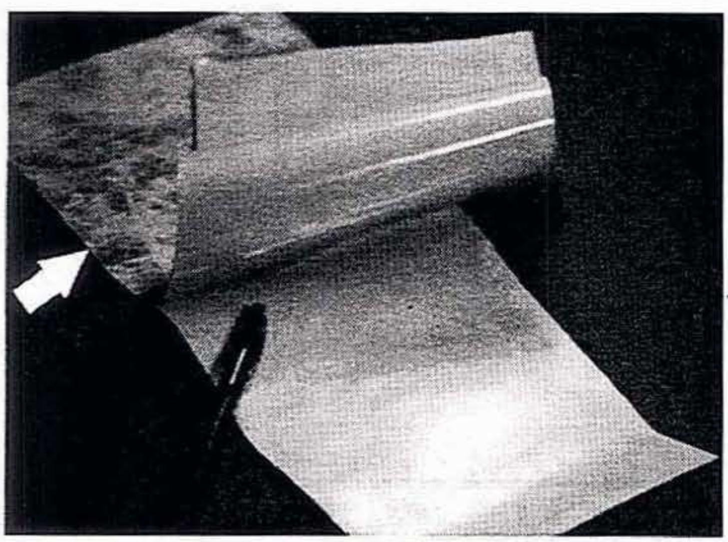

Figure 6 *View of an "unbonded flap." The seam occurs where indicated by the arrow. The ink pen is laying on the unbonded flap, which extended underneath the membrane for several inches beyond the lap.*

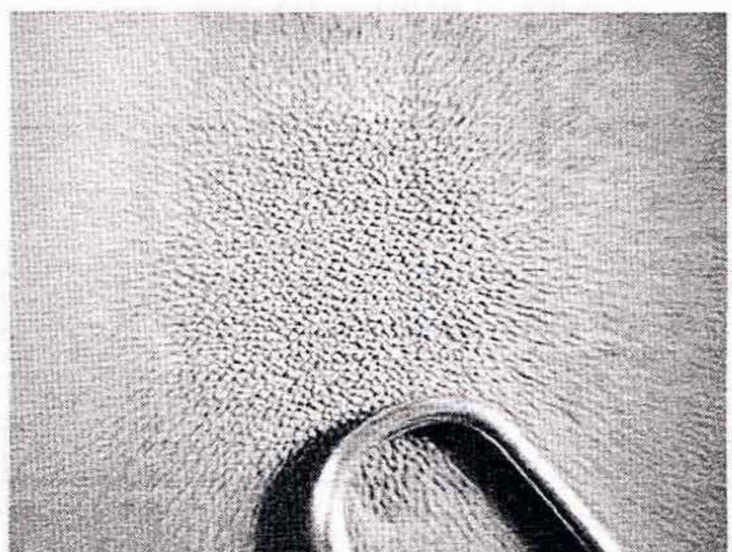

Figure 7 *Surface checking of a 7.5 year old mechanically attached unreinforced shattered PVC roof system (90/91-23). A paper clip shows the scale of the checking, which is visible with the naked eye.*

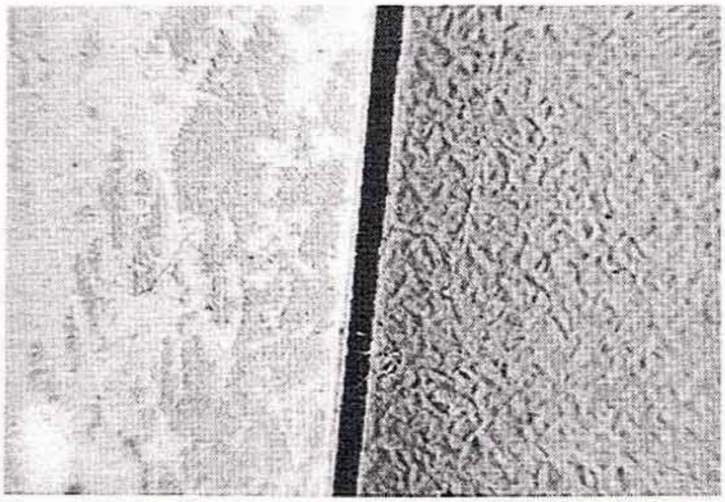

Figure 8 *Side-by-side comparison of two samples from the same shattered ballasted unreinforced PVC roof system. The sample on the right side has an "orange peel" surface. This sample was fairly clean. The sample on the left was fairly smooth. This sample had a good deal of dirt on it (most of whi... as washed off prior to taking the photo).*

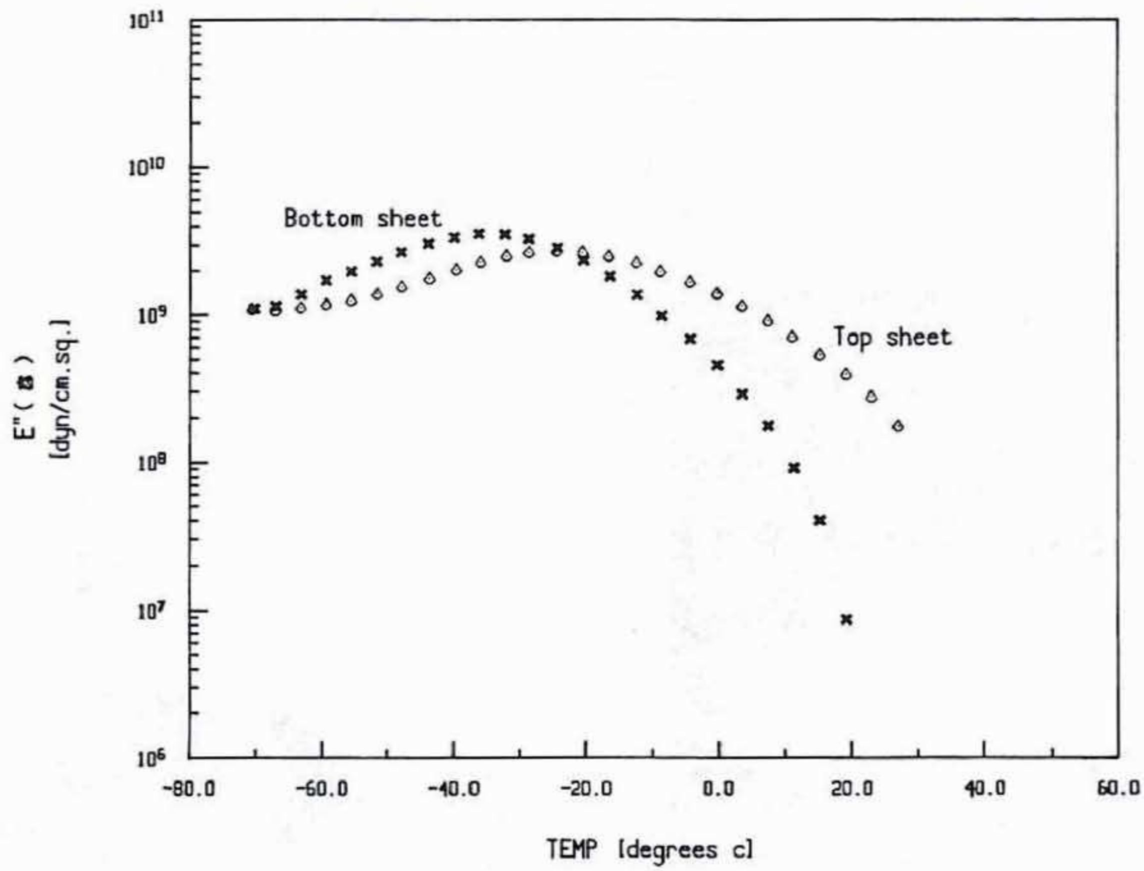

Figure 9 *E" curves obtained for the "Top" and "Bottom" sheet of a shattered PVC roofing membrane.*

Figure 10 Shrinkage of an unreinforced ballasted PVC roof system: the ballast has moved inward away from the parapet by a few feet. Also, the exhaust pipes have been slightly pulled over, and a portion of the base flashing has pulled away from the parapet (see arrow). These conditions are potential early warning signs of shattering.

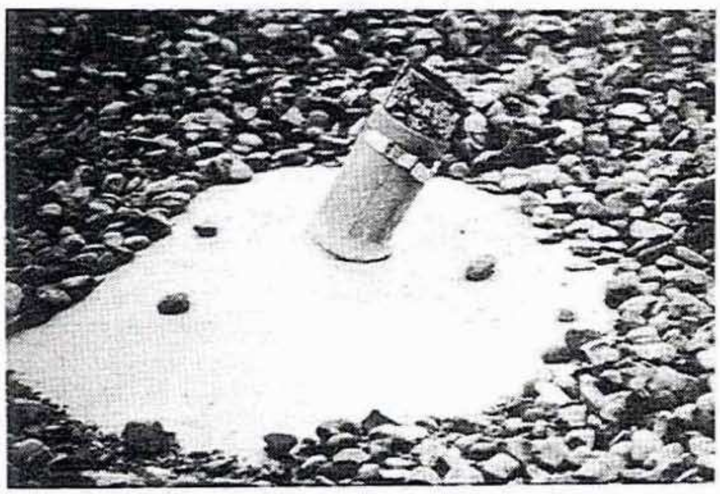

Figure 11 Shrinkage of an unreinforced ballasted PVC roof system has resulted in displacement of this plumbing vent. This too, is a potential early warning sign of shattering.

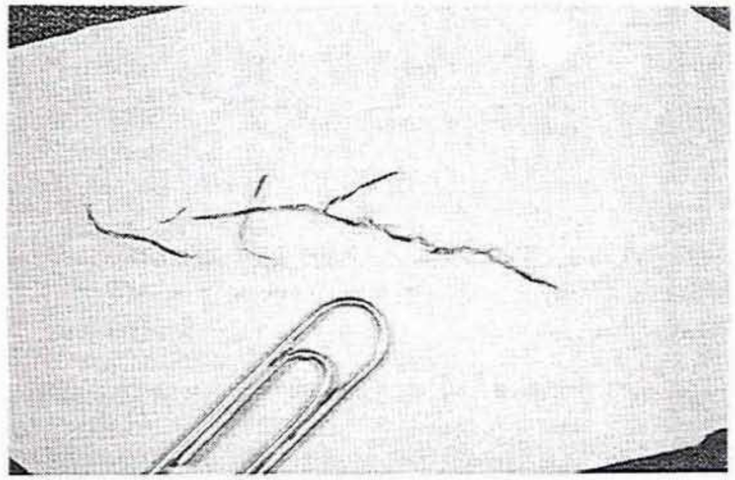

Figure 12 Cracked reinforced mechanically attached PVC membrane roof system. The crack extends completely through the membrane. However, the reinforcement that bridges the crack was not ruptured. Surface checking is also visible to the naked eye. The roof had approximately 10 similarly cracked areas, none of which appeared to be due to abuse or neglect. This sample was 35 mils thick. Unlike shattering, cracking may be repairable, and it is not a catastrophic failure. This job was approximately 12 years old when the problem was reported in 1991. A strengthened ASTM D 4434 is needed to differentiate between those sheets that offer a long service life from those that do not.