FIELD EVALUATION AND LABORATORY TESTING OF PVC ROOF SYSTEMS

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Beginning in the late 1970s, the use of PVC roof systems gained widespread acceptance. Performance of PVC systems, however, has varied greatly. As a result, PVC systems have come under close scrutiny because of the potential for sudden catastrophic failure. The catastrophic failure mode has included susceptibility to impact/hail damage and sudden shattering.

Numerous factors have affected the performance of PVC roof systems. These factors include geographical use, formulation, method of installation, and manner of membrane fabrication.

Field evaluation of PVC systems may offer limited information concerning the potential for performance problems. Microscopic examination and laboratory testing of characteristics such as mil thickness, tensile strength, elongation, plasticizer content, specific gravity, and durometer hardness may offer greater understanding into the performance of PVC assemblies.

Data from laboratory testing of numerous roof assemblies of different ages and in use in different geographical locations will be used with a modeling program to predict PVC membrane performance.

PVC roof systems were initially developed and marketed in the late 1950s and early 1960s in Europe by various major chemical companies.[1] In the 1970s, these companies introduced PVC roof systems into the United States as an alternative to conventional built-up roof assemblies.

The initial systems utilized nonreinforced PVC sheets that were held in place by ballast and attached at perimeter and field flashing locations. Installation variations consisting of mechanically attached nonballasted assemblies were introduced. In the late 1970s and early 1980s, some companies began to market reinforced PVC sheets that were also installed in ballasted and mechanically attached assemblies.

Throughout the 1980s, some of the nonreinforced PVC sheets failed in shatter mode. As a result of these shatter problems, the National Roofing Contractors Association (NRCA) and the Single Ply Roofing Institute (SPRI) issued a joint document, *Shattering of Aged Unreinforced PVC Roof Membranes.*[2]

The sudden catastrophic failure phenomena of shattering introduced the roofing industry to a new type of roof failure. This type of roof failure was so sudden and without warning that in some cases the building owner would go from having a relatively trouble-free roof to simply having no roof. The subsequent leakage, interior damage, and disruption of building activities in some cases resulted in substantial financial losses.

The NRCA/SPRI document discusses the issue of PVC shattering. The PVC shattering phenomena is usually accompanied by a rapid decrease in air temperature. PVC sheets have also failed suddenly when subjected to impacts during a hailstorm. The consequential building damage in a hail event can be just as devastating as that of a shatter failure.

The NRCA/SPRI document lists early visual warning signs, including embrittlement and displacement of wood nailers and flashings. The warning signs listed by the NRCA/SPRI document, however, may not always be present. The document also indicates that shattering may occur without warning.

This document offers evaluation methods beyond visual examination. Examination of numerous projects utilizing PVC membranes has shown that clear-cut visual warning signs are not always observable. The roofs, however, are subject to catastrophic failure.

KEYWORDS

Elongation, embrittlement, failure, field, fracture, hail, hardness, impact, lap, mil thickness, modulus of elasticity, nonreinforced, plasticizer, polyvinyl chloride (PVC), reinforced, shade, shatter, shrinkage, specific gravity, and tensile strength.

OBJECTIVES

Physical properties of all roof systems change with age and exposure. The change in the physical properties of a roof membrane may be a function of many factors. A few factors that may affect the physical properties of a PVC membrane include chemical formulation stability, geographical location, heat and ultraviolet radiation exposure, and other products used in conjunction with the membrane and roof slope.

During the course of a roof system's anticipated life, a building owner should be able to rely upon that roof to sufficiently retain its physical properties to the point of adequate performance. When a roof system's physical properties change to such a degree that the system is subject to sudden catastrophic failure, the building owner should have some method available to assist in the prediction of potential roof problems and should be able to take appropriate action. Ideally, as a roof system wears out, initial minor leaks should occur rather than a sudden and catastrophic roof failure.

The definition of *failure* is always subject to debate. One person's failure may be another person's nuisance. Situations where severe leakage through a roof system can be expected with every rainstorm can be considered a failure. Widespread, uncontrolled leakage throughout a facility has been deemed by most experts in the roofing industry as a failure.

Dr. Rene Dupuis attempted to numerically categorize types of roof failures with a *1* though *4* system.[3] The fourth level of failure, uncontrolled widespread leakage, is clearly defined as a total catastrophic-type failure. An attempt to educate, warn, and take appropriate actions to avert this type of failure was one purpose of the 1990 NRCA/SPRI document.

At present, the manufacturers of PVC roof systems have not publicly provided building owners with any method, other than visual examination, to predict when a roof is subject to a failure. The objective of this paper is to provide additional methods of analysis that may assist in evaluating an in-place PVC membrane. The methods of evaluation discussed within this paper were derived from laboratory analysis and inspection of various projects throughout the United States.

BACKGROUND

PVC membranes consist primarily of a PVC resin modified with a plasticizer, coupled with other additives. The other additives can include colorant, fire retardant, biocide, lubricants, ultraviolet stabilizers, and ultraviolet absorbers. Depending on the vintage, the PVC membrane may be nonreinforced, reinforced with random fibers, or reinforced with a scrim. Manufacturers have their own proprietary chemical formulations for their particular membrane. Some manufacturers have also reported that ongoing improvements or enhancements have been made to their chemical formulations over the years.

Initial nonreinforced PVC membranes introduced into the United States were approximately 0.76 mm (30 mil) to 0.89 mm (35 mil) thick. These initial membranes did not perform well and were quickly replaced with thicker [1.14 mm (45 mil) to 1.27 mm (50 mil)], products used primarily in ballasted applications. Thicker [1.27 mm (50 mil) to 1.52 mm (60 mil)] nonreinforced membranes were introduced and began to be used in mechanically attached assemblies. As these systems gained widespread use throughout the United States, manufacturers of the various products began to introduce reinforced PVC membranes in the late 1970s and early 1980s.

As early as 1981, the U.S. Army identified potential problems of PVC embrittlement and shrinkage.[1] The U.S. Army concluded that these problems could be minimized with the addition of reinforcement and improved ultraviolet- and evaporation-resistant membranes. In the mid-1980s, information began to develop about the actual chemical processes of the loss or evaporation of plasticizer within the PVC membranes. In a 1985 paper, "Roof Coverings Made of PVC Sheetings: The Effect of Plasticizers on Lifetime and Service Performance,"[4] Gerhard Pastuska indicated that the evaporation of plasticizer might be important in some countries, but not as critical in northern Europe. The paper discusses some of the physical property effects resulting from plasticizer loss. This includes a loss of thickness, an increase in modulus of elasticity, an increase in hardness, along with the shrinkage of material.

The performance of PVC membranes appears to vary depending upon geographical location. In performing an evaluation of unballasted membranes in Europe, Reiner Schoepe concluded that 10-year-old PVC membranes showed very little change in relevant properties such as strength, elongation, thickness, rigidity, and hail impact resistance.[5]

Throughout the 1980s, the performance of various PVC systems within the United States varied greatly. In 1992, William C. Cullen reported in NRCA's *Project Pinpoint Analysis: Ten-Year Performance Experience of Commercial Roofing 1983-1992* that the use experience of PVC between 1983 and 1992 was 3.3 percent.[6] This same group represented 10.7 percent of the problems experienced by contractors. The PVC group had the highest problem-to-use ratio of all roof systems listed in the report. This included BUR asphalt, BUR coal tar, EPDM, modified bitumen, and others.

During the early 1990s, Cash[7] and Paroli, Smith, and Whelan[8] observed the inclusion of reinforcement and speculated that it would help to prevent the shattering phenomena.

As experience developed with PVC products, the manufacturers switched from the nonreinforced to the reinforced membrane sheets currently marketed. The addition of reinforcement material was believed to stabilize the membrane and reduce the danger of shrinkage. Some manufacturers also stated that the inclusion of reinforcement enhanced the impact/hail resistance of the PVC membrane.

PROCEDURES

In order to evaluate the current condition of an in-place PVC roof system, various procedures can be used. One method is to semiannually perform a detailed visual examination and look for the early warning signs of embrittlement or displaced wood nailers as listed in the NRCA/SPRI document. The tautness or pulled flashings may be fairly easy to observe in ballasted applications. In many cases, however, a visual examination alone may be not be adequate.

Tautness or pulled flashings are the result of shrinkage. As the membrane loses plasticizer, shrinkage will occur, thus resulting in the stressed flashing situation. Visual tautness or pulled flashings within mechanically attached systems may not be as readily apparent. The uniform points of attachment may restrict the membrane to the point that obvious shrinkage is not apparent. When examining mechanically attached PVC systems, the lack of the NRCA/SPRI warning signs does not necessarily indicate that the roof is not highly susceptible to catastrophic failure.

Reinforced assemblies may also be somewhat deceiving. The presence of the reinforcement restricts shrinkage caused by plasticizer loss. A situation may develop in which a membrane has lost plasticizer, has hardened and become somewhat embrittled, but has gone through very little shrinkage because of the restriction of the reinforcement.

An alternative method to visual examination includes the removal of samples followed by laboratory testing. The purpose of testing is to compare the current condition of the in-place membrane to some type of norm.

Part of the problem, however, determining what the norm should be for the in-place membrane. In 1982, NRCA recommended to its members in *Bulletin 13* that a small portion of the original roof membrane be retained with the job file for purposes of physical property characterization. For testing purposes, it would be extremely beneficial if some of the original, unused membrane was available; however, this is a rare occurrence.

Other comparisons of the in-field membrane's physical properties can be made to the manufacturer's original marketing literature. Many of the PVC manufacturers list the minimum and expected physical property values for their various products. These values include tensile strength, elongation, hardness, and cold brittleness. Many of these laboratory procedures are identified with ASTM test numbers. Comparison can also be made to ASTM D 4434, First Edition. It should be realized, however, that the manufacturer's original marketing numbers and the numbers within ASTM D 4434 are minimum consensus standards for physical property characteristics of new products.

If original material is not available, comparison of the in-place field membrane can be made with portions of the membrane that have had a lesser degree of exposure. This would involve removing samples that include unexposed portions of the laps that have not been heat- or solvent-welded. The exposed field material can then be compared to the relatively protected lap material. This provides data on the comparative difference between exposed and relatively unexposed portions of the membrane. Some research in this area has been performed and is discussed in "Shattering of Unreinforced PVC Membranes: Problem, Phenomenon, Causes and Prevention."[8]

Other comparisons of lab data can be made between areas of the membrane with direct sun exposure to areas primarily located in solar shaded areas. This could include membrane areas on the north side of parapet walls, enclosed screened areas, or areas immediately north of penthouses.

Once testing has been performed, the data from an existing roof can be compared to roofs with known histories. As a part of this research, samples were removed from various roofs. The performance record of the aged roofs were placed in four general categories: 1) satisfactory, 2) impact damaged but repairable, 3) impact damage failure, and 4) shatter failure (Figure 1).

Different categories of lab test data from 26 separate projects with known histories were collected. The projects, labeled A through Z, were from 16 states and included products from four different manufacturers. Several different lab testing procedures were involved from project to project. Not all projects were subjected to the same laboratory tests (Figure 2).

Mil Thickness

The relatively simple test of measuring mil thickness can provide useful insight into a product's condition. This method of testing simply involves measuring the percentage decrease in thickness that occurs from the unexposed lap sample to the exposed field sample. For example, if the field has an average of 45 mils and the lap has an average of 50 mils, a 5-mil decrease, or 10 percent reduction in membrane thickness, has occurred. This can then be compared to various projects

Rating	General Performance Features
1) Satisfactory	Minimal to no leakage, various degrees of shrinkage, no shattering, no impact/hail damage
2) Impact damaged but repairable	Some damage from impacts but repairable
3) Impact damage failure	Irreparable catastrophic damage
4) Shatter	Catastrophic failure

Figure 1. Ratings used to categorize the performance records of aged roofs.

	Rating			
	1	2	3	4
Roof System	Satisfactory	Impact Damaged but Repairable	Impact Damage Failure	Shatter
B-NR	C N O J Q Z		D L U Y	A F
MA-NR	R	B P	E I S T X	G M
B-R	V	H		
MA-R			K W	

Figure 2. B-NR, ballasted nonreinforced; MA-NR, mechanically attached nonreinforced; B-R, ballasted reinforced; MA-R, mechanically attached reinforced, Projects A-Z.

with known histories of performance (Figure 3).

In reviewing the data, there is a general increase in the difference of the mil thickness between the lap and field samples for roofs in a failure mode. It should be noted, however, that in some cases (e.g., the category B-NR, Rating 1), a fairly substantial change in percentage has occurred, and the roofs are performing satisfactorily. Part of the explanation for this is that the conditions for roof failure (i.e., rapid change in temperature or impact/hail damage) simply have not occurred to such a degree to cause problems with these particular roofs.

Tensile and Elongation

Many PVC manufacturers list tensile strength and elongation characteristics in their marketing literature. As a PVC membrane ages and experiences a loss of plasticizer, these properties change. Generally, there tends to be a decrease in the elongation rate as plasticizer decreases. In some circumstances, there may even be an increase in the tensile strength as the product ages. Figure 4 shows the tensile/elongation strength characteristics for exposed membrane versus nonexposed portions of the lap for three different projects where a shatter failure had occurred with nonreinforced products.

A shatter failure is shown in Figure 5.

The unexposed lap portions have elongation rates in the 400 percent range, whereas the field portion of these particular shatter failure samples have elongation rates of approximately 200 percent. There is clearly a substantial difference between the properties of the unexposed, unbonded lap and the field. If one observes the same type of numbers in Figure 6 for nonreinforced impact/hail failures, the same type of

	Performance History			
	1	2	3	4
Roof Type	Satisfactory	Impact Damaged but Repairable	Impact Damage Failure	Shatter
B-NR	8.88%	XXXX	6.8%	16.32%
MA-NR	4.31%	5.0%	9.51%	12.08 %
B-R	XXXX	8.26%	6.52%	XXXX
MA-R	XXXX	XXXX	10.66%	XXXX

Figure 3. Comparison of percentage of reduction in mil thickness for different roof types with various performance histories. (XXXX=no data.)

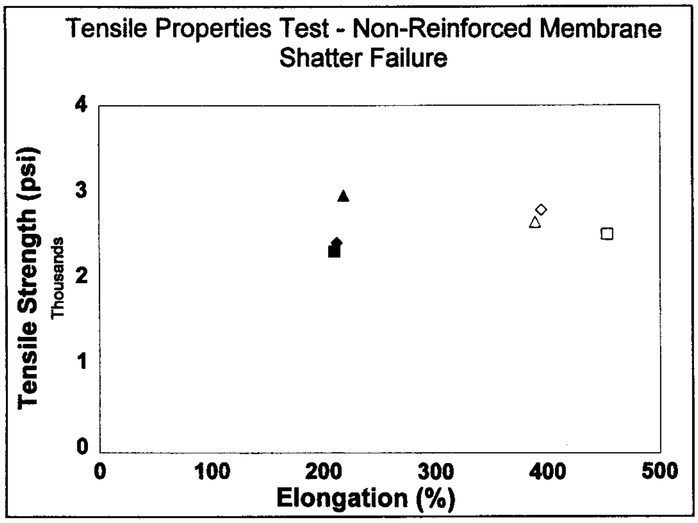

Figure 4. Tensile/elongation rates for nonreinforced shattered membranes.

Figure 5. Shatter failure, mechanically attached, nonreinforced membrane.

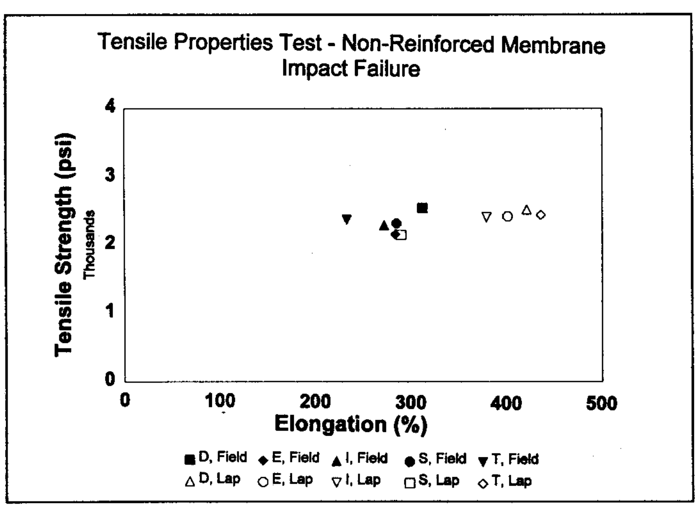

Figure 6. Tensile/elongation nonreinforced membrane impact failure.

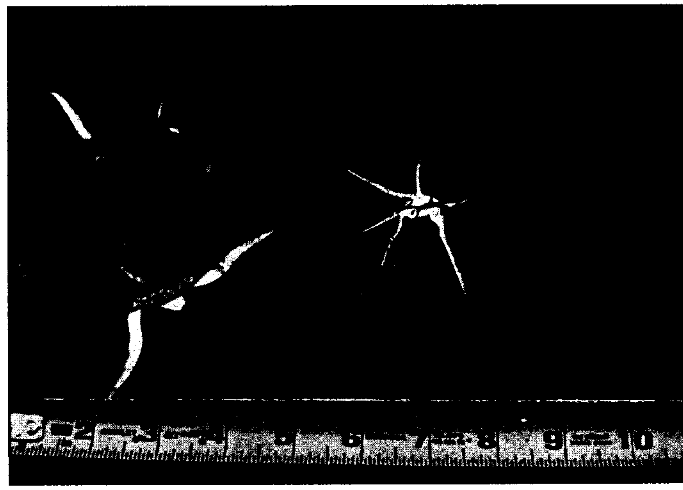

Figure 7. An example of PVC membrane failure.

trend occurs; however, the elongation rate for the failed field samples range between 200 percent and 300 percent.

The type of failure shown in Figure 7 has occurred in storms with hail measuring 25 mm (1 inch) in diameter.

Figure 8 combines the data of elongation rates for shatter and impact/hail failures. Except for Project T, the shatter failures have a greater difference of elongation rate between the exposed field and unexposed, unbonded laps.

This researcher, to date, has not observed a shatter failure in a reinforced-type product. Impact/hail damage failures; however, have occurred with some reinforced PVC membranes. Figure 9 shows resulting damage to a reinforced PVC membrane from hail impact. Based on this researcher's observations, if there has been a sufficient loss of plasticizer from a reinforced membrane, susceptibility to impact/hail damage increases.

Earlier research in STP 959 1988 for ASTM indicated that new single-ply membranes had a fairly high degree of impact/hail resistance.[9] Obviously, as some membranes age, the impact/hail threshold substantially decreases.

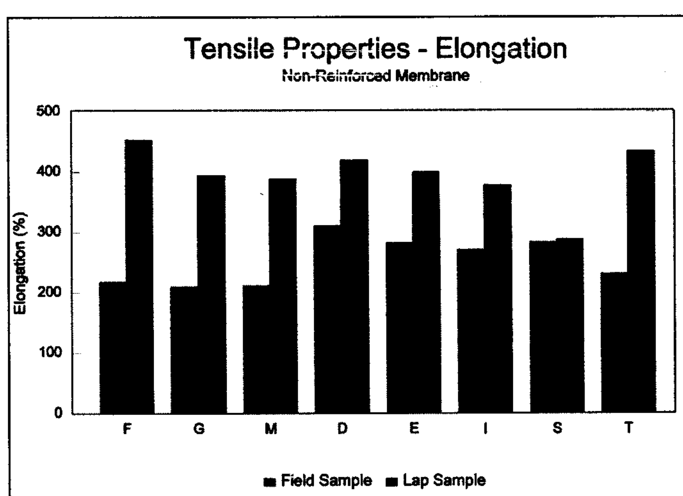

Figure 8. Elongation percentage comparison field lap samples in shatter and impact failure mode.

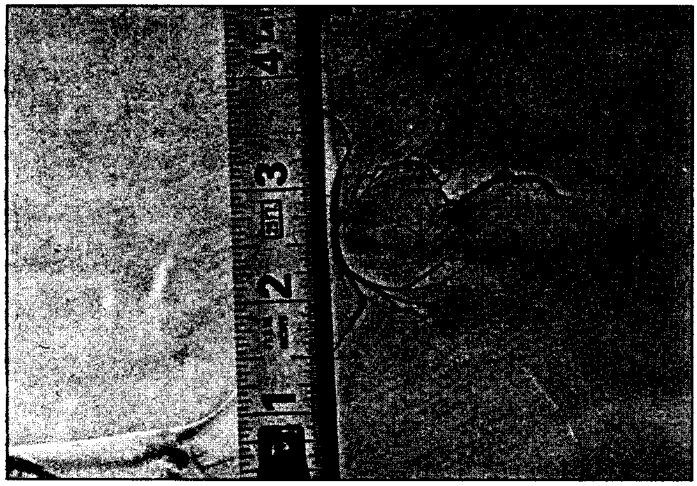

Figure 9. Impact damaged reinforced PVC membrane.

Plasticizer Variation

ASTM D 3421 involves the complete extraction of plasticizer from a PVC membrane sample. A comparison was made between the plasticizer content in the field samples vs. unexposed, unbonded lap samples. The percentage decrease in plasticizer from the lap to field is noted in Figure 10. Figure 10 indicates that in roofs performing satisfactorily, there is the least amount of variation in plasticizer content between lap and field. As one progresses to the impact/hail damage and shatter failure modes, the variation in plasticizer content between lap and field becomes more significant.

Specific Gravity

PVC sheets are composed of PVC, plasticizer, and other additives. As the plasticizer migrates from the membrane, the specific gravity of the membrane will increase. If one examines the specific gravity of the membrane in the exposed field vs. the specific gravity of the unexposed, unbonded lap sections, an increase in the percentage difference between the two occurs as the roof ages (see Figure 11). It should be noted that even though there is an increase in the specific gravity, some roofs may have satisfactory performance. These roofs may not have been subjected to weather conditions, such as rapid changes in temperature or exposure to sufficient impact/hail, to result in unsatisfactory performance.

A comparison between the plasticizer content and specific gravity of various samples is shown in Figure 12. In performing a regression analysis, one sees the correlation between specific gravity of a membrane sheet and its plasticizer content. The plasticizer content test, ASTM D 3421, has been discontinued and is somewhat more difficult to run than a specific gravity test.

Percentage drop in plasticizer from lap to field				
	1	2	3	4
Roof Type	Satisfactory	Impact Damaged but Repairable	Impact Damage Failure	Shatter
B-NR	xxx	xxx	xxx	xxx
MA-NR	3.27%	xxx	10.41%	17.25%
B-R	xxxx	xxx	xxx	xxxx
MA-R	xxx	xxx	17.04%	xxxx

Figure 10. Percentage variation from lap to field and plasticizer content.

Specific gravity increase between field and lap				
	1	2	3	4
Roof Type	Satisfactory	Impact Damaged but Repairable	Impact Damage Failure	Shatter
B-NR	2.96%	xxx	2.53%	xxx
MA-NR	xxx	xxx	2.78%	3.14%
B-R	xxxx	xxx	xxx	xxxx
MA-R	xxx	xxxx	xxx	xxxx

Figure 11. Percentage specific gravity increase between field and lap.

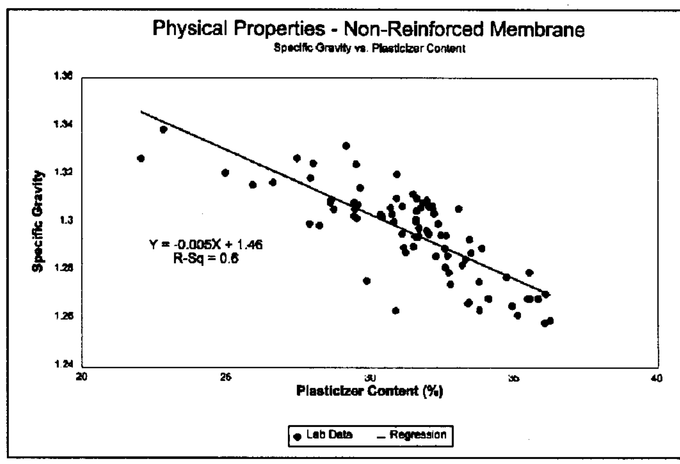

Figure 12. Specific gravity/plasticizer content comparison.

The observance of a loss of plasticizer coupled with an increase in specific gravity was noted in a U.S. Army report, *Long-Term Field Test Results for Polyvinyl Chloride (PVC) Roofing.*[10]

Durometer Hardness

Most of the PVC membrane manufacturers list a durometer hardness for their product in the original marketing literature. This particular test is typically performed in accordance with ASTM D 2240. As the PVC membranes are exposed, the hardness of the membranes increase. If one examines the relative durometer hardness of the exposed field to the unexposed, unbonded lap, there generally appears to be an increased percentage difference between the field and laps. Note the overall data as shown in Figure 13.

	1	2	3	4
Roof Type	Satisfactory	Impact Damaged but Repairable	Impact Damage Failure	Shatter
B-NR	3.55%	xxx	4.17%	5.81%
MA-NR	2.43%	xxx	5.92%	5.31%
B-R	xxxx	6.41%	2.30%	xxxx
MA-R	xxx	xxxx	3.52%	xxxx

Figure 13. Durometer hardness increase from lap to field.

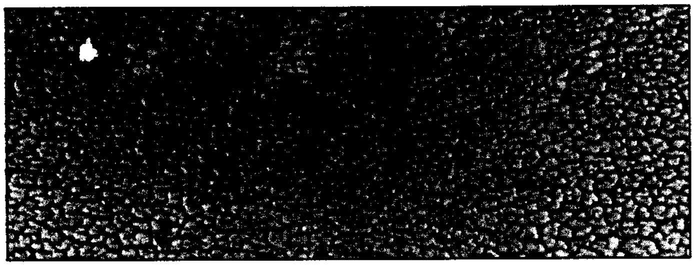

Figure 14. 10x magnification, nonreinforced PVC membrane, puncture failure.

Microscopic Examination

For some PVC membrane sheets, microscopic examination can provide insight into the condition of the PVC membrane. This is particularly evident and a useful examination for mechanically attached, nonreinforced roof assemblies. Figure 14 is a sample taken from a nonpunctured area of a roof that experienced puncture/hail failure. In membrane sheets that have had known failures from shattering and impact/hail damage, this checkered/brain-type appearance has occurred. This type of visual observation was reported in "Shattering of Unreinforced PVC Roof Membranes."[8] Other methods of analysis documented in this article included thermal mechanical techniques to characterize roof membranes.

CONCLUSIONS

The addition of reinforcement material to PVC membrane sheets has clearly assisted in preventing the wall-to-wall catastrophic-type shattering experienced with nonreinforced membranes. Improved chemical formulations may also be assisting in extending the life of PVC membranes. These changes should increase the net anticipated life of PVC membrane systems.

At some point in time, the physical properties of reinforced PVC membranes will diminish with age and exposure. Although an aged reinforced PVC system may not be a candidate for shattering, the system may be vulnerable to impact/hail damage. The vulnerability of some systems to impact/hail damage after aging can result in situations in which catastrophic failures will occur. This situation can occur even if reasonable performance has been enjoyed by the building owner.

Visual examination of some PVC roof systems may not be adequate to provide owners with sufficient information to make reasonable roofing decisions. Utilization of various laboratory testing techniques may assist the owner in making informed roof management decisions.

A protocol for evaluating the condition of reinforced and nonreinforced PVC roof systems could include visual observations, membrane sample collection, and laboratory analysis (mil thickness, tensile/elongation, plasticizer loss, specific gravity, durometer hardness, and microscopic examination). The results of these tests should be compared to original marketing literature and any additional information provided by the manufacturer to determine if significant changes have occurred involving membrane physical properties, membrane composition, and membrane condition.

As described within this paper, a comparison of the physical properties of the unexposed lap portions of the PVC membrane to exposed field sections may provide valuable insight into the relative condition of the roof system. Other techniques would involve thermal mechanical analysis as listed in "Shattering of Unreinforced PVC Roof Membranes."[8]

In order for building owners to be cognizant of when their roofs are reaching a point of susceptibility to failure, manufacturers should monitor the long-term performance of their systems and provide timely information as to long-term performance characteristics. This type of information may provide a consumer with sufficient information to allow for a planned, timely replacement of membranes. Manufacturers of PVC roof systems should also provide consumers with appropriate technical information, such as failure histories, evaluation techniques, and performance criteria to assist the owner in making informed roof management decisions.

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