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Long-Term Field Test Results for Polyvinyl Chloride (PVC) Roofing

by
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The U.S. Army Construction Engineering Research Laboratories (USACERL) has recently completed a 10-year field exposure study of the performance of polyvinyl chloride (PVC) roofing membrane materials. Membranes from three manufacturers were installed at Chanute Air Force Base, IL, Dugway Proving Ground, UT, and Fort Polk, LA. A major difference in the roof constructions was that, at Chanute, the membranes were ballasted whereas, at Dugway and Fort Polk, they were mechanically attached except for one case which was fully adhered. The intent of the USACERL study was to compare the results of laboratory tests of membrane properties with field performance. Periodically over the 10 years, USACERL visually inspected the roofs to evaluate their performance and removed samples for laboratory characterization of selected mechanical and physical properties. The performance was generally satisfactory at Dugway and Fort Polk, whereas problems related to membrane shattering and splitting occurred at Chanute. Statistical analysis of the 10-year data set was conducted. Because of the less-than-satisfactory performance at Chanute, the data analysis was focused on determining whether changes in any of the measured properties were consistently different for samples from Chanute than for samples from Dugway and Fort Polk. The results did not discriminate between the performance of the PVC membranes at Chanute and those at Dugway and Fort Polk. For example, it was observed that all samples at the three sites lost plasticizer during the exposure period. Two of the three membrane samples from Chanute did not lose significantly more plasticizer than those from Dugway or Fort Polk.

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Foreword

This study was conducted for Headquarters, U.S. Army Corps of Engineers under Project 4A162784AT41, "Military Facilities Engineering Technology"; Work Unit A-044, "Improved and New Roofing for Military Construction." The technical monitor was Rodger Seeman, CEMP-ET.

The work was performed by the Materials Science and Technology Division (FL-M) of the Facilities Technology Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was David M. Bailey. Walter J. Rossiter, Jr., and James A. Lechner are with the National Institute of Standards and Technology. Ellen G. Segan is Acting Chief, CECER-FL-M; Donald F. Fournier is Acting Operations Chief, CECER-FL; and Alvin Smith is Chief, CECER-FL. The USACERL technical editor was Linda L. Wheatley, Technical Resources Center.

COL James T. Scott is Commander and Acting Director, and Dr. Michael J. O'Connor is Technical Director of USACERL.

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1 Introduction

Background

The use of synthetic single-ply and polymer-modified membranes as alternatives to built-up roofing (BUR) has increased dramatically since the late 1970s. Recent estimates show that single plies and modified bitumen materials now account for about 65 percent of the total low-sloped roofing market (Cullen 1993). This increase has occurred despite improvements in BUR materials and construction specifications. Recognizing the importance of having performance information on alternative membrane roofing, the U.S Army Corps of Engineers (HQUSACE) has asked the Construction Engineering Research Laboratories (USACERL) to investigate such systems for Army facilities (Marvin et al. 1979).

One of the roofing membrane materials selected for long-term field testing was polyvinyl chloride (PVC) (Rosenfield 1981). In 1982 and 1983, test roofs were installed on buildings in three different areas of the country: Chanute Air Force Base, IL, Dugway Proving Ground, UT, and Fort Polk, LA (designated Sites 1, 2, and 3, respectively). Products from three manufacturers (designated Samples 1, 2, and 3) were selected for the study, which was designed to track the performance of the installed roofing over 10 years (Marvin et al. 1979). Laboratory testing of mechanical and physical properties was scheduled for membrane samples taken every 6 months for the first 2 years and annually thereafter. The exact times of removal of the sample sets varied from the scheduled times because of unforeseen contracting constraints.

Two interim papers have been published on the progress of the study. In 1987, Rosenfield and Wilcoski reported early test results along with a description of the study design. In 1990, Foltz and Bailey published results through 6 years of field exposure. Since then, data for 4 more years of exposure have been gathered and the entire PVC data set statistically analyzed.

Objective

The objective of this report is to document long-term results of a field test program to evaluate PVC roofing membrane. The results of the statistical analysis of the data set are compared to the reported field performance of the roofing systems.

Approach

The following procedures were used to achieve the objective of this study:

1. Roof systems for a 10-year field evaluation were selected based on earlier USACERL studies.
2. A test plan was developed using standard test methods published by the American Society for Testing and Materials (ASTM).
3. Test sites were selected.
4. Test guide specifications were developed.
5. Construction of the test roofing systems was monitored.
6. Test data were collected for 10 years after construction.
7. Test roofs were inspected visually once a year.

Mode of Technology Transfer

Information generated by this study will impact on Corps of Engineers Guide Specifications (CEGS) 07555, Polyvinyl Chloride (PVC) Roofing as well as aid in the development of test methodologies for assessing the in-service performance of PVC roofing.

Metric Conversion Factors

U.S. standard units of measure are used throughout this report. A table of metric conversion factors is presented below.

1 in.	=	25.4 mm
1 ft	=	0.305 m
1 sq ft	=	0.093 m^2
1 lbf	=	0.138 kg m
1 psi	=	6.89 kPa

2 Description of Test Program

Description of Test Roofs

The three sites for the test program were selected for geographic and climatic diversity. A project building was chosen at each site. Each building roof was divided into three sections, allowing membrane material from each of the three manufacturers (Samples 1, 2, and 3) to be installed. The roof sections ranged in area from 6,930 to 13,600 sq ft.

The roofing systems at Chanute AFB consist of a poured-in-place concrete deck, a two-ply organic felt and asphalt vapor retarder, and 2-1/2 in. of aluminum foil-faced isocyanurate foam board in two layers, loose laid. The PVC membranes were installed loose laid and ballasted.

At Dugway Proving Ground, the systems consist of a poured-in-place concrete deck, 3 in. of aluminum foil-faced isocyanurate foam board in two layers mechanically fastened to the deck without a vapor retarder. The Sample 1 membrane was mechanically fastened with the membrane adhered to discs of PVC material; the Sample 2 membrane was mechanically fastened with the membrane adhered to steel battens; the Sample 3 membrane was fully adhered.

The systems at Fort Polk consist of a tongue-and-groove wood plank deck and 4-1/2 in. of aluminum foil-faced expanded polystyrene insulation board in two layers that are mechanically fastened to the decks without a vapor retarder. Sample 1 membrane was mechanically fastened along one edge of each sheet using fasteners and washers; Sample 2 membrane was mechanically fastened with the membrane adhered to steel battens; Sample 3 membrane was fully adhered to the fiberboard surface of composite insulation board.

Table 1 gives a summary description of the roof systems. A discussion of the construction of the test roofs can be found in USACERL Technical Report M-343 *Construction of Experimental Polyvinyl Chloride (PVC) Roofing* (Rosenfield 1984).

ASTM Categorization of PVC Membranes

In 1985, ASTM issued standard specification D 4434 that categorized PVC membranes into Types I, II, and III, with Type II subdivided into two grades:

Type I:	Unreinforced sheet
Type II:	Grade 1 - Unreinforced sheet containing fibers
	Grade 2 - Unreinforced sheet containing fabrics
Type III:	Reinforced sheet containing fibers or fabric.

The Type II terminology may be misleading as fibers and fabrics are used to "reinforce" polymeric sheets.* By way of explanation, the ASTM Standard D 4434 contains a note that reads:

> (F)abrics or fibers may be incorporated into a production process, for example, as a carrier, without appreciably affecting such physical property characteristics of the finished product as tensile strength or ultimate elongation, but may provide other desirable characteristics, such as dimensional stability.

Membranes used in this field study included all three types (Table 1). Sample 1 was a Type I product at Chanute and a Type III product at Dugway and Fort Polk. Sample 2 and Sample 3 were Type I and Type II products, respectively, at each of the three exposure locations. When the study began, most manufacturers specified an unreinforced membrane (either ASTM Type I or Type II) for ballasted systems. As shown in Table 1, the three ballasted membrane systems at Chanute Air Force Base were either Type I or Type II membrane materials. Field experience with PVC roofing has shown that some unreinforced PVC membranes (ASTM Type I) have undergone splitting, cracking, and shattering in service, particularly those that are ballasted (Paroli, Smith, and Whelan 1993). As a consequence, ballasted PVC systems are seldom specified today.** As will be discussed later in the report, the ballasted systems at Chanute (Site 1) experienced splitting and related problems.

ASTM D 4434 also contains a requirement that the minimum thickness of a PVC roofing sheet be 0.045 in. Note in Table 1 that all samples in the study were in conformance with this requirement.

* As this report is being written, ASTM D 4434 is under revision, and this terminology is expected to change.

** ASTM task group actions on the revision of D 4434 have proposed the elimination of Type I membrane material because it is no longer used for roofing.

Table 1. Summary of the PVC roof constructions.

Sample No.	Test Site No.	Deck	Insulation	Vapor Retarder	Membrane Securement	Membrane ASTM Type[a]	Seam Weld	Thickness mm (In)
1	Chanute 1	Concrete	Isocyanurate	2-ply organic	Ballasted	I	Heat	1.2 (0.046)
2	Chanute 1	Concrete	Isocyanurate Slip sheet/kraft	2-ply organic	Ballasted	I	Heat	1.3 (0.050)
3	Chanute 1	Concrete	Isocyanurate Perlite board	2-ply organic	Ballasted	II	Heat	1.2 (0.049)
1	Dugway 2	Concrete	Isocyanurate	none	Mech. attach (disks)	III	Heat	1.2 (0.047)
2	Dugway 2	Concrete	Isocyanurate Slip sheet/kraft	none	Mech. attach (battens)	I	Heat	1.2 (0.047)
3	Dugway 2	Concrete	Isocyanurate	none	Adhered	II	Heat	1.2 (0.047)
1	Fort Polk 3	Wood	Polystyrene Slip sheet/fbgls	none	Mech. attach (washers)	III	Solvent	1.2 (0.047)
2	Fort Polk 3	Wood	Polystyrene Slip sheet/kraft	none	Mech. attach (battens)	I	Solvent	1.4 (0.055)
3	Fort Polk 3	Wood	Polystyrene Fiberboard	none	Adhered	II	Heat	1.2 (0.048)

[a]See the following paragraph for a description of the ASTM categorization of membrane types.

Test Program

The USACERL test program was designed to determine changes in mechanical and physical characteristics of the various PVC membranes at the three exposure locations. An initial set of tests was performed on each of the different materials cut from the membranes after installation to establish material characteristics of the new (unaged) membranes. For Sites 1 and 2, initial sampling was performed upon completion of the roofs. For Site 3, initial sampling occurred 3 months after the membranes were installed. Subsequently, samples were taken from each material at each site on a periodic basis, the target schedule being every 6 months for the first 2 years and annually thereafter. Five membrane sections each measuring 1 sq ft were removed from each roof section: four from near each of the corners and one from the center. Final sampling was performed at 116, 95, and 113 months, respectively, for Sites 1, 2, and 3. These times were approximately 9¾, 8, and 9½ years, respectively.

Table 2 lists the properties measured and the ASTM test method designation. The tensile, elongation, and tear resistance tests were conducted only on membrane Types I and II. The ply adhesion test was only performed on the Type III membrane (Sample 1 at Sites 2 and 3) as a measure of the adhesion of the PVC resin to the reinforcement.

The testing design was to conduct five measurements (one for each of the five membrane sections) of each property per material per exposure location per point in time. This was generally followed. But, for some properties of the initial (i.e., unaged) samples, more than five measurements were made. In contrast, in the case of abrasion loss, specific gravity, water absorption, and water vapor transmission, only one initial measurement was performed. And, as will be evident from the plots to follow, some properties were not measured for every section removed from the roofs.

Table 2. Properties measured and ASTM test methods used.

Property Measured	ASTM Method [8]	ASTM Volume*
Plasticizer Content	ASTM D 3421	discontinued
Plasticizer Loss	ASTM D 1203	08.01
Tensile Strength	ASTM D 882	08.01
Elongation	ASTM D 882	08.01
Tear Strength	ASTM D 1004	08.01
Ply Adhesion	ASTM D 413	09.01
Abrasion Loss	ASTM D 3389	09.02
Thickness	ASTM D 1593 or ASTM D 751	08.01 09.02
Specific Gravity (Relative Density)	ASTM D 792, Procedure A-1	08.01
Water Vapor Transmission	ASTM E 96	04.06
Water Absorption	ASTM D 570	08.01
Dimensional Stability	ASTM D 1204	08.01
Seam Strength (Shear)	ASTM D 882	08.01
Seam Strength (Peel)	ASTM D 1876	15.06

*Indicates the volume of the ASTM Book of Standards where the test method is described.

3 Visual Inspections

In general, each test roof was inspected by USACERL research personnel annually. The observations recorded over the first 6 to 7 years of the study indicated that the PVC roof membranes were performing satisfactorily. No observations caused concern about the watertightness of the roof or other aspects of membrane performance. Seams reported (Cullen 1993) as a source of significant performance defects with synthetic membrane materials performed satisfactorily at all sites. The minor problems noted during these early inspections were generally associated with items such as details around flashings and penetrations, drains, gutters, and debris.

As an example of a nonmembrane related problem, the roof areas near the north and south edges of the Chanute installation, where Samples 1 and 2 were installed, were highly sloped. The ballast material in those areas constantly slides from membrane and roof, stretching the membrane and damaging the edge detail and gutter. Alteration of the edge detail stopped the ballast from sliding into the gutter, but did not prevent stretching of the membrane (Figure 1). Although not membrane related, as noted below, this problem apparently contributed to membrane damage at a later date.

During the 5-year inspection of the roofing at Chanute, the membranes showed evidence of shrinkage as they were seen to have tightened in place. The shrinkage was not extensive enough to raise concerns about membrane performance. However, in December 1989 during record cold temperatures, after about 7 years of exposure, Sample 1 at Chanute catastrophically shattered across the entire membrane (Figure 2). The membrane was replaced. The shattering was typical of that experienced by other PVC roof membranes during the late 1980s (Paroli, Smith, and Whelan 1993). All such failures have reportedly occurred with unreinforced membranes, many of which were ballasted. The failures have been attributed to stress build up in the membranes due to shrinkage resulting from plasticizer loss. Unreinforced membranes would be more likely to have catastrophic failures because reinforcement might be expected to arrest splits or cracks. The increased risk of failure with ballasted systems has been discussed by Pastuska (1985), who concluded that a mixture of water, mud, microorganisms, and oxygen on the ballasted membrane surface tends to increase plasticizer loss.

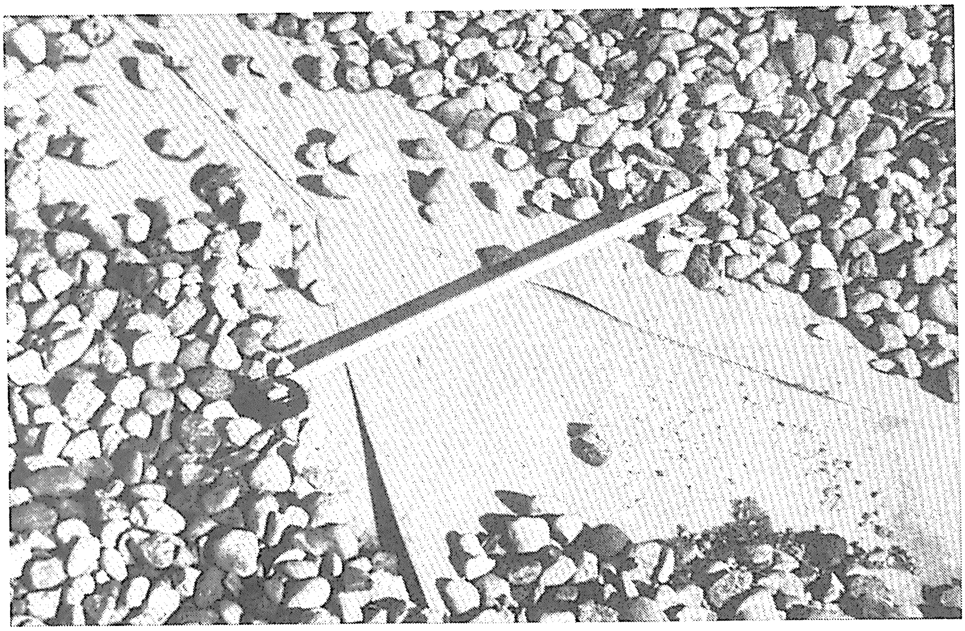

Figure 1. Stretching of the membrane.

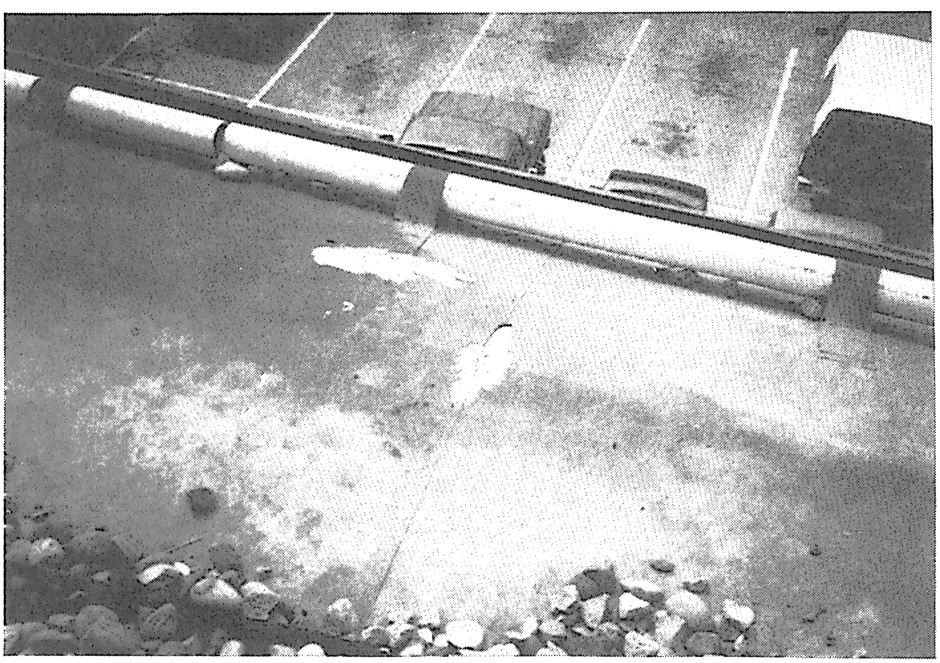

Figure 2. Shattering of the membrane of Sample 1 at Chanute.

For 10 years the inspections at Chanute indicated satisfactory performance of membrane Samples 2 and 3. In the spring of 1994 (after about 11 years of service), both samples experienced problems. In the case of Sample 2, the membrane shattered in the area along the south edge of the building where it had been stretched by the sliding ballast (Figure 3). Although the area of shattering was limited, the entire membrane was replaced because of the risk that the unshattered section of the membrane might also fail catastrophically. In the case of Sample 3, two splits occurred in the field of the membrane. The splits were repaired as the majority of the membrane was considered still functional.

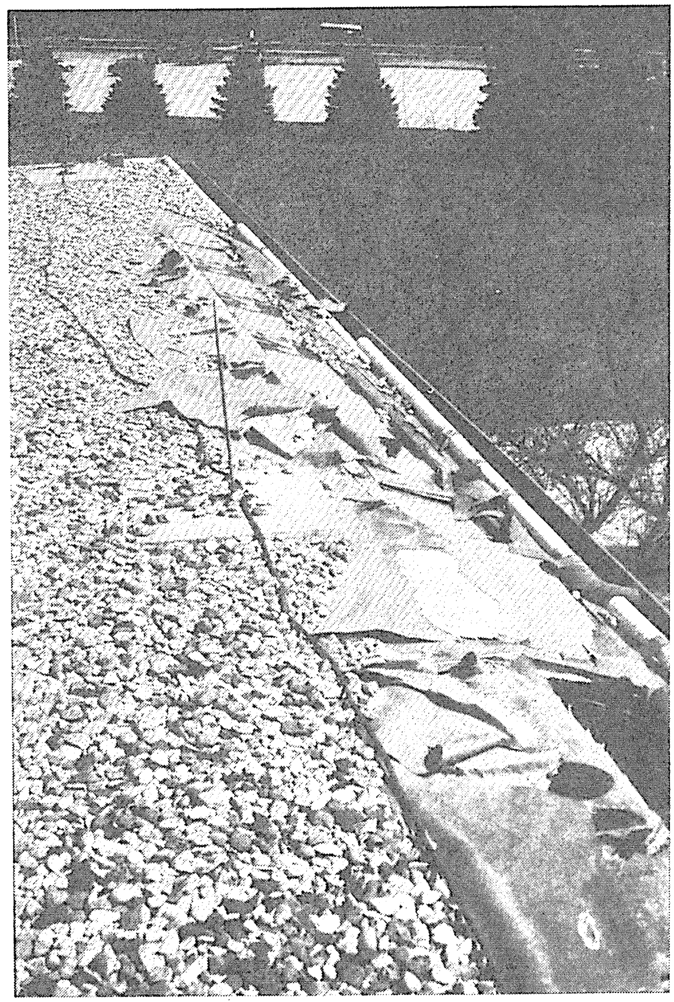

Figure 3. Sample 2 at Chanute shows the shattered membrane where it was stretched by the sliding ballast.

Performance of all PVC membranes at Dugway (Site 2) was satisfactory through 1989 (about 8 years of service). However, shortly thereafter, nonroofing related work on the roof resulted in punctures and cuts of the membranes to the extent that repair was not considered practical. Consequently, the Dugway membranes were replaced.

The three membranes at Fort Polk (Site 3) generally have performed satisfactorily for more than 10 years. However, the roof has not been leak free. Some mechanical fasteners used for securing the roofing backed out from the deck and punctured the membranes. Fastener backout without membrane puncture was observed about 3 years into the study, but it was late into the study when the puncturing occurred. No judgment was made as to whether the puncturing should be assigned to poor fastener performance or poor membrane performance. The punctures have been repaired, and the roof is still functional.

4 Analysis of Test Data

Treatment and Presentation of Data

This chapter presents the data and their analyses. The data are presented graphically (Figures 4 through 16)* and, for each property, one plot gives the measured value versus time for a given membrane sample (Samples 1, 2, and 3) and installation site (Sites 1, 2, and 3). Thus, in general, nine plots are given for each property (three samples times three sites) in each figure. For comparison, all nine plots are given on a single page. By examining a set of plots across a row, any differences between the samples at a fixed site are observed. Likewise, by considering a set of plots down a column, the effect of site on a fixed sample is seen. All individual data points are plotted, but the plots do not distinguish overstrikes.

The analysis of the data was conducted using a linear model:

$$\text{response} = A_0 + A_1 t$$

where t = time in months
A_0 = a constant (the intercept)
A_1 = a constant (the slope).

This model was selected after reviewing the plots of measured property value versus time, which in general did not support the selection of a more complex model. Although exceptions were noted (for example, see Figure 9, Sample 3 at Site 1), the number of exceptions was not sufficient to warrant the use of other models. In some cases where a nonlinear model might be suggested by the plots, scatter in the data with increasing age was considered partially responsible for this appearance (for example, see Figure 9, Sample 3 at Site 1 vs Site 3, page 32).

Each plot contains the best-fit straight line for a set of data for each sample at each site. In slightly over half the analyses, the slope was statistically different from zero (i.e., the magnitude of the slope was at least three times greater than its standard deviation). In some cases where the slope was not statistically different from zero, the

* Figures begin on page 23.

data exhibited no appreciable time dependence. In others, the apparent change in property over time was overshadowed by the large uncertainty in the estimated slope due to a large scatter in the data.

To aid interpretation of the results, tables for each property (except for plasticizer content) were prepared to summarize:

- the initially measured average property value (M_i)
- the estimate of the true value at initial time (A_0)
- the slope of the line (A_1)
  Note: In the tables where the units for A_1 are [(the units for A_0) x months^{-1}] either for the S.I. (metric) or customary values.
- whether the slope was statistically different from zero; the column contains a "yes" whenever the magnitude of the estimated value was at least three times its standard deviation
- an estimate of the percent change in the property over 100 months calculated using the model for each data set. The indicated uncertainty in the estimated percent change represents one standard deviation.

The estimated percent change in a property was taken as an indicator of how much that property changed during the study. A nominal study period of 100 months was used in the estimate because it was within the range of time over which the sampling at the three sites was performed. The estimate of percent change in property value provides a uniform means of comparing the properties as a function of sample and site and determining those which underwent the greatest change over time.

A summary of the variability in the descriptors M_i, A_0, and A_1 is given in the Appendix. The variations listed are one standard deviation.

The following sections contain the tables and plots of the data analyses. Comments on key observations for each set of plots and table are given for each property. Many of these comments focus on the change in properties of the ballasted roofs at Chanute (Site 1) because of the less-than-satisfactory performance at this site. The intent was to determine whether changes in any of the measured properties were consistently different for samples from Chanute than for samples from Dugway and Fort Polk. Additionally, in reviewing the results of the seam strength tests, a point of evaluation was whether solvent-welded seams performed differently than heat-welded seams. As a note regarding all properties, it was observed that the measured average property value (M_i) and the estimate of the true value at initial time (A_0) generally were in agreement.

Plasticizer Content and Plasticizer Loss

The first properties presented are those related to plasticizer loss. However, the measurement of plasticizer content was not included in the study until 1989, when it was conducted only on retained initial samples from Chanute and Fort Polk, and those cut from all roofs after about 5 years of exposure. Initial samples from Dugway had not been retained. The membrane materials specified at Dugway and Fort Polk were the same but probably from different lots. Thus, the initial plasticizer contents of the Dugway materials might be expected to be comparable to those at Fort Polk.

The following comments may be made about the plasticizer content results given in Table 3:

- The data set is limited in that measurements were made only for the original membrane material and after the roofs had been in service for about 5 to 6 years. Thus, only trends can be noted.
- For each of the three samples, the measured initial plasticizer contents were essentially the same at Chanute and Fort Polk.
- Assuming that, for each of the three samples, the initial Dugway materials were comparable to those at Chanute and Fort Polk, all PVCs lost plasticizer over the 5 to 6 years of exposure. The range was from about 15 to 30 percent.
- In most cases, little difference was seen between many of the plasticizer content values after 5 to 6 years of exposure. For six of the nine measurements, the average plastizicer contents of the aged samples ranged from 23 to 26 percent. The others were higher.

Table 3. Plasticizer content measurements (ASTM D 3421).

SITE	PLASTICIZER CONTENT, % by mass		
Membrane Age	Sample 1	Sample 2	Sample 3
Site 1 (Chanute)			
original	31 ± 3	32 ± 2	35 ± 1
68 months	23 ± 2	26 ± 1	25 ± 1
Site 2 (Dugway)			
original	----	----	----
62 months	26 ± 1	28 ± 2	31 ± 1
Site 3 (Fort Polk)			
original	30 ± 1	31 ± 1	34 ± 1
60 months	25 ± 1	26 ± 2	29 ± 1

Note: This property was not measured for unaged samples from Site 2.

- The ballasted aged Sample 1 at Chanute showed the lowest average plasticizer content; this was the membrane that experienced catastrophic shatter. The exposed aged Sample 1 at Fort Polk had the second lowest average value; this membrane has performed satisfactorily. Considering the variation in the data, these two aged samples had essentially the same plasticizer content after about 5 to 6 years of service. Chanute is located in the North; whereas Fort Polk is in the South.
- Similarly, the average plasticizer content for aged Sample 2 at Chanute was the same as that of aged Sample 2 at Fort Polk. Chanute experienced problems; whereas Fort Polk has performed satisfactorily.
- In the case of Sample 3, the ballasted membrane at Chanute lost more plasticizer than the exposed membranes at Dugway and Fort Polk.

The plasticizer loss test "drives" plasticizer from the sheet material. The loss value is determined by heating the specimen removed from the roof and measuring the mass lost during heating. If the amount lost during the test decreases with time of field exposure, it may be that the plasticizer was lost during field exposure.

The following comments may be made about the plasticizer loss results given in Table 4 and Figure 4:

- For Site 2, no initial data were available to include in the analysis. The first measurements were made when the Site 2 samples were 52 months old. For the available data at Site 2, none of the slopes of the regression lines were statistically different from zero. This may be an indication that the plasticizer available for loss during the test may have reached a constant value when the series of tests of Site 2 samples began. Note, in a similar observation, that the samples at Sites 1 and 3 showed little variation in the plasticizer loss values measured after 48 months.

Table 4. Summary of plasticizer loss results (ASTM D 1203).

Sample No.	Site No.	M_I (% mass)	A_0 (% mass)	A_1	Stat. Sign.	Est. Change in 100 Months (%)
1	1	8.1	7.8	-0.0810	yes	-103 ± 16
1	2	2.5	2.8	-0.0019	no	-7 ± 39
1	3	4.9	4.4	-0.0145	no	-33 ± 14
2	1	7.7	6.6	-0.0053	yes	-80 ± 19
2	2	2.7	3.2	-0.0087	no	-27 ± 32
2	3	4.4	3.7	-0.0192	yes	-51 ± 18
3	1	4.3	3.8	-0.0273	yes	-72 ± 17
3	2	1.5	1.6	-0.0032	no	-2 ± 4
3	3	1.8	1.5	-0.0031	no	-21 ± 22

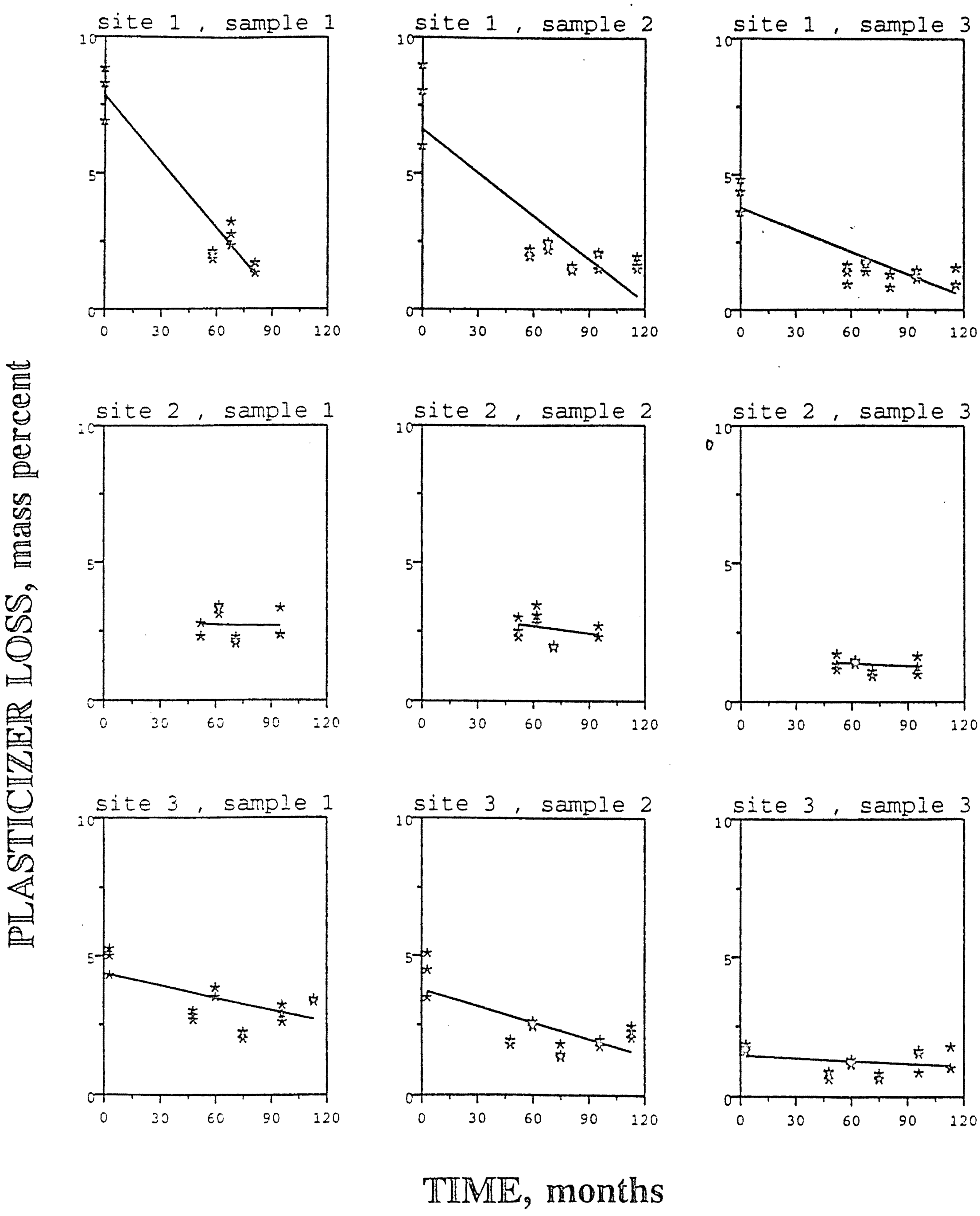

Figure 4. Results of the plasticizer loss tests.

- For each sample, the values of plasticizer loss were greater (by a factor of about 2) at Site 1 than at Site 3. Reasons for this observation (e.g., material variability, test method variability, or unknown factors related to shipping, installation, or initial outdoor exposure) are not known.
- For Samples 1 and 2, the final values of plasticizer loss were lower at Site 1 (ballasted membranes) than at Site 3 (exposed membranes). For Sample 3, the final values were about the same at Site 1 and at Site 3.
- A comparison of the estimated percent change over 100 months for the samples at Sites 1 and 3 has little meaning considering the greater initial values at Site 1 versus Site 3. It is noted that, for the samples, four of the six regression lines had slopes statistically different from zero.

Tensile Strength

The following comments may be made about the tensile strength results given in Table 5 and Figure 5:

- Initial tensile strength for Sample 1 was stronger than Sample 2, which was stronger than Sample 3.
- With the exception of Sample 2 at Site 2, the slopes of the regression lines were positive, indicating an increase of strength with time. With the exception of Sample 2 at Site 3 and Sample 3 at Site 2, the slopes were statistically different from zero.

Table 5. Summary of tensile strength results (ASTM D 882).

Sample No.	Site No.	M_i (psi)	A_0 (psi)	A_1	Stat. Sign.	Est. Change in 100 Months (%)
1	1	2412	2429	9.6	yes	40 ± 10
2	1	2286	2226	4.05	yes	18 ± 3
2	2	2104	2169	-1.52	yes	-7 ± 2
2	3		2112	0.29	no	1 ± 2
3	1	1776	1686	11.42	yes	68 ± 11
3	2	1493	1485	1.417	no	9 ± 3
3	3	1677	1647	2.66	yes	16 ± 3

Note: This property was not measured for Sample 1 at Sites 2 and 3.

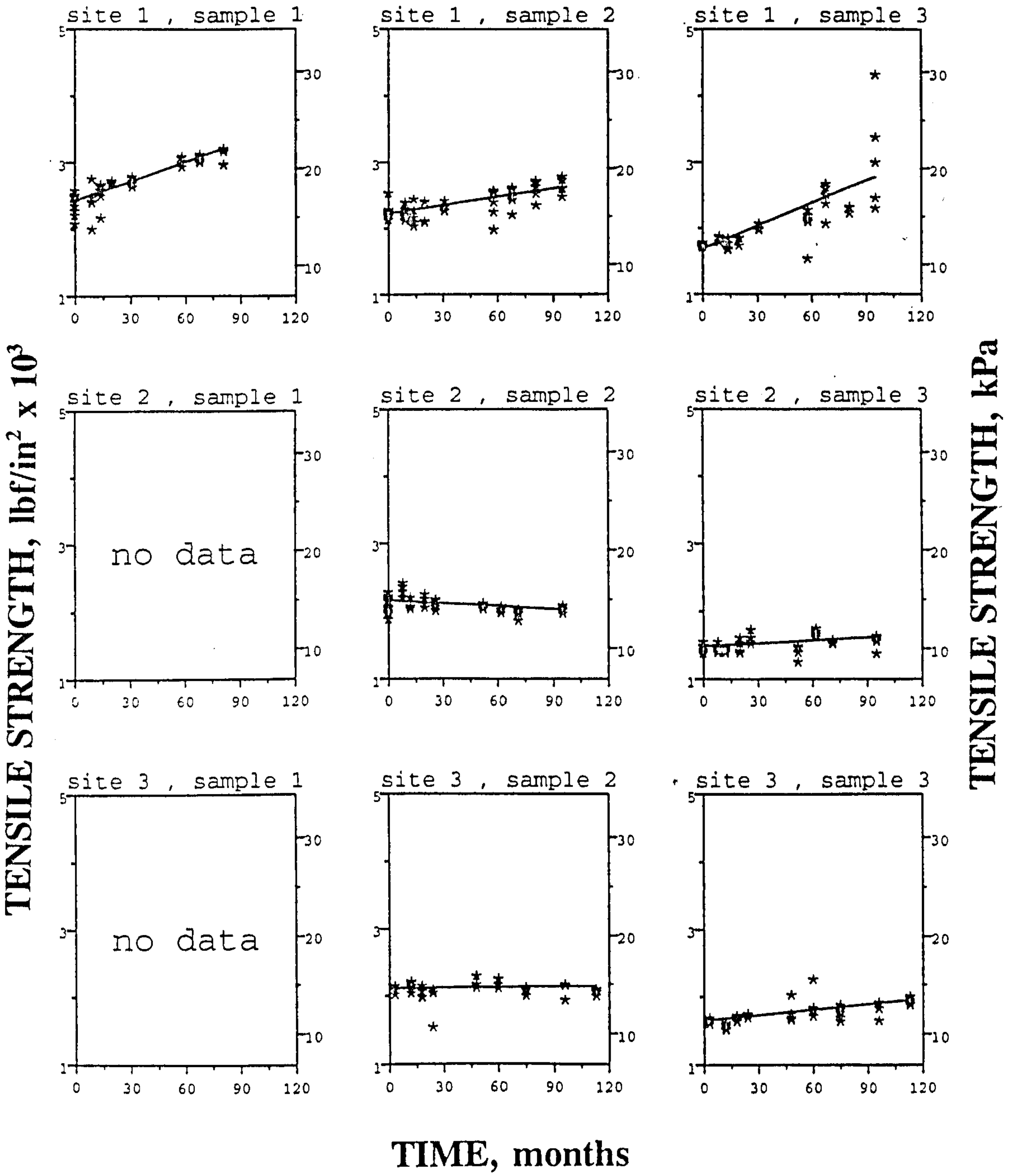

Figure 5. Results of the tensile strength tests.

- Sample 3 at Site 1 showed the largest estimated percent increase over time (68 percent). The data for this sample had considerable scatter at the longer exposure times, which may have contributed to the estimated increase.
- For the data set, the three samples at Site 1 showed the largest estimated percent increase. Site 1 membranes were ballasted and experienced problems in service.
- The largest estimated percent change for a nonballasted system was found for Sample 3 at Site 3. This value (16 percent) was comparable to that (18 percent) found for the ballasted Sample 2 at Site 1.

Elongation

The following comments may be made about the elongation results given in Table 6 and Figure 6:

- For all samples, the initial elongations were comparable, ranging from about 230 to 290 percent.
- All samples showed a decrease in elongation over time. The slopes of the regression lines were statistically different from zero in six of the seven cases. The exception was Sample 3 at Site 2, which was nearly significant. (The estimated value of the slope was 2.6 times its standard deviation.)
- The ballasted Sample 3 at Site 1 had an estimated decrease that was greater than those of the exposed Sample 3 at Sites 2 and 3.
- The ballasted Sample 2 at Site 1 had an estimated decrease that was less than those found for the nonballasted Sample 2 at Sites 2 and 3.

Table 6. Summary of elongation results (ASTM D 882).

Sample No.	Site No.	M_i (%)	A_0 (%)	A_1	Stat. Sign.	Est. Change in 100 Months (%)
1	1	269	264	-0.50	yes	-19 ± 6
2	1	290	285	-0.42	yes	-15 ± 4
2	2	259	265	-0.55	yes	-21 ± 3
2	3	256	254	-0.62	yes	-24 ± 4
3	1	254	256	-0.99	yes	-39 ± 11
3	2	253	245	-0.41	no	-17 ± 7
3	3	232	235	-0.26	yes	-11 ± 4

Note: This property was not measured for Sample 1 at Sites 2 and 3.

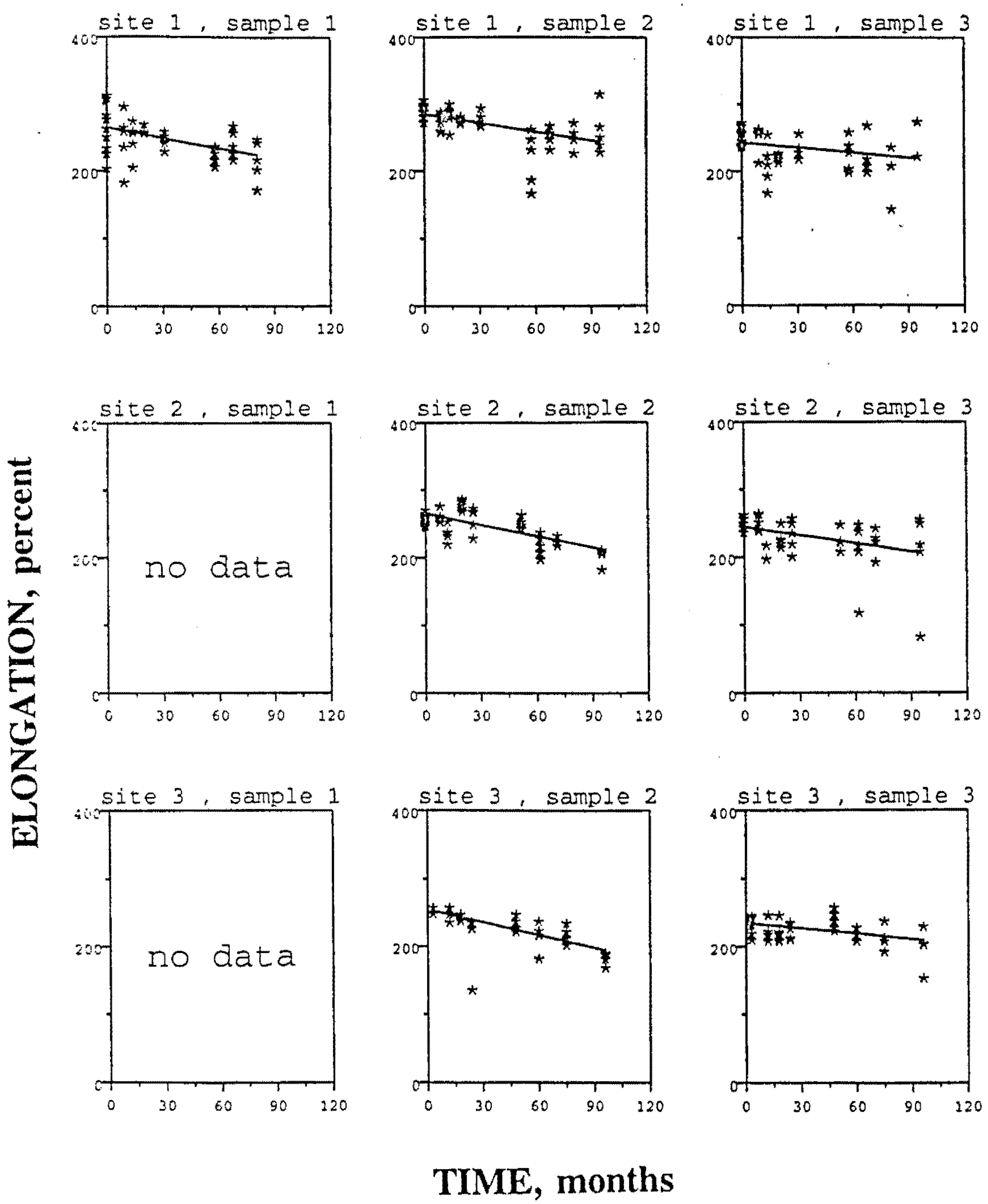

Figure 6. Results of the elongation tests.

Tear Strength

The following comments may be made about the tear strength results given in Table 7 and Figure 7:

- Sample 3 had the greatest initial tear strength; Sample 2 had the lowest value.
- All samples showed an increase in tear strength over time. With the exceptions of Samples 2 and 3 at Site 2, the slopes of the regression lines were statistically different from zero.
- The ballasted roofs at Site 1 showed the greatest estimated increase; the values were more than twice the estimated change for any of the nonballasted roofs at Sites 2 and 3.

Ply Adhesion

Ply adhesion was measured only for the reinforced Sample 1, Type III membrane materials at Sites 2 and 3.

The following comments may be made about the ply-adhesion results given in Table 8 and Figure 8:

- Initial ply adhesion was about 2.5 times greater for Site 2 than Site 3. This may be a measure of material variability for Sample 1.
- Ply adhesion at Site 3 increased over time with a slope statistically different from zero; whereas this was not the case at Site 2.
- Data collected for samples taken after about 24 months showed more scatter than the earlier data.

Table 7. Summary of tear strength results (ASTM D 1004).

Sample No.	Site No.	M_i (lbf)	A_0 (lbf)	A_1	Stat. Sign.	Est. Change in 100 Months (%)
1	1	14.1	13.4	0.100	yes	75 ± 8
2	1	12.8	12.6	0.057	yes	45 ± 5
2	2	12.8	13.0	0.005	no	4 ± 3
2	3	11.1	11.7	0.025	yes	21 ± 5
3	1	15.8	15.0	0.073	yes	49 ± 6
3	2	15.8	15.5	0.015	no	10 ± 6
3	3	16.1	15.7	0.029	yes	18 ± 4

Note: This property was not measured for Sample 1 at Sites 2 and 3.

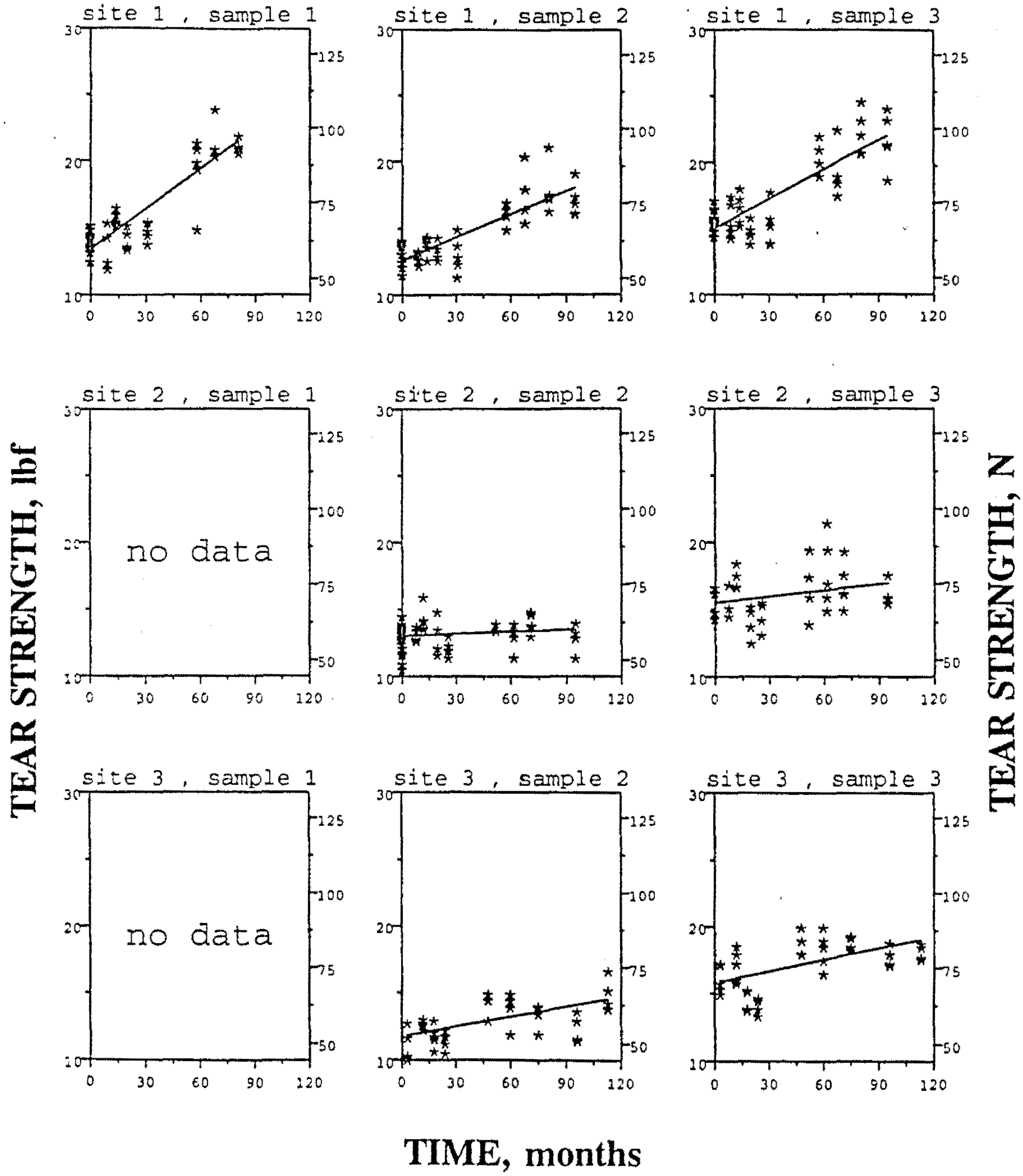

Figure 7. Results of the tear strength tests.

Table 8. Summary of ply-adhesion results (ASTM D 413).

Sample No.	Site No.	M_i (lbf)	A_0 (lbf)	A_1	Stat. Sign.	Est. Change in 100 Months (%)
1	2	19.8	18.8	0.025	no	13 ± 15
1	3	7.8	7.5	0.117	yes	155 ± 40

Note: This property was only measured for Sample 1 at Sites 2 and 3.

Abrasion Loss

The following are key comments and observations for the abrasion loss results given in Table 9 and Figure 9:

- For abrasion loss, it is not meaningful to use an estimated percent change as an indicator of relative performance between the samples and sites because the initial property values are quite close to zero. Thus, slopes of the regression lines are used as a comparison of relative performance.
- All samples showed an increase in the amount of mass lost upon abrasion (i.e., decrease in abrasion resistance) as time increased. However, the slopes of the regression lines were statistically different from zero in only two-thirds of the cases.
- The ballasted Sample 1 at Site 1 displayed the greatest slope. The ballasted Sample 3 had the second greatest slope but it was not statistically different from zero due to the data scatter at the longer exposure times
- The slope for the ballasted Sample 2 at Site 1 was comparable to those for the unballasted Sample 2 at Sites 2 and 3.

Thickness

The following comments may be made about the thickness results given in Table 10 and Figure 10:

- With the exception of Sample 1 at Site 3, the thickness of the samples at all sites decreased over time, ranging from 5 to 18 percent. In these cases, the negative slope of the regression line was statistically different from zero. It is not known whether the reduction in thickness was associated with factors such as relaxation shrinkage, loss of plasticizer, erosion of the surface, or, in the case of ballasted membranes, creep associated with the load of the ballast.
- The ballasted samples at Site 1 experienced the greatest estimated decrease in thickness.

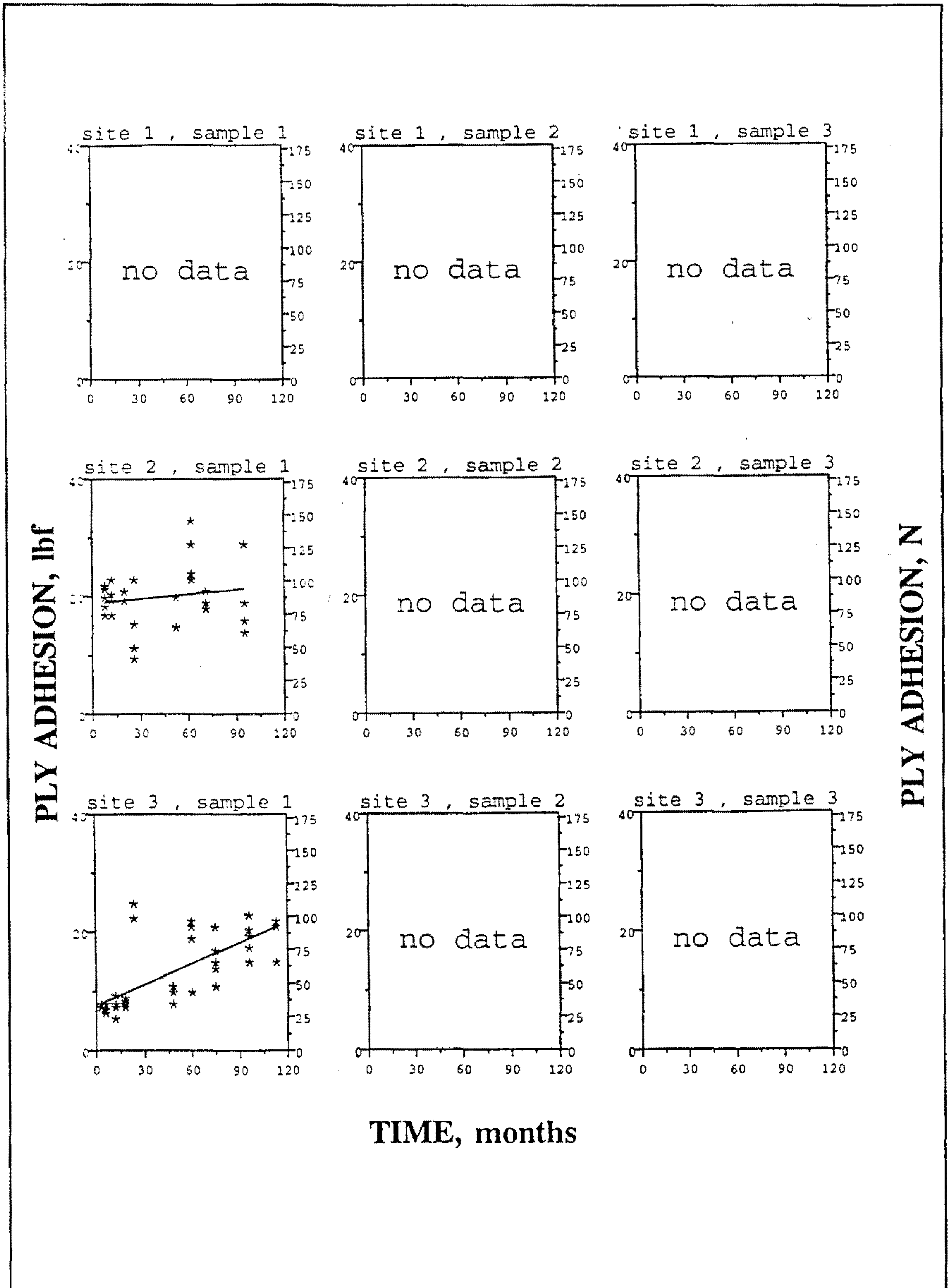

Figure 8. Results of the ply-adhesion tests.

Table 9. Summary of abrasion loss results (ASTM D 3389).

Sample No.	Site No.	M_i (g per 2000 rev)	A_0 (g per 2000 rev)	A_1	Stat. Sign.	Est. Change in 100 Months (%)
1	1	0.011	-0.026	0.0022	yes	NA
1	2	0.013	0.013	0.0004	no	NA
1	3	0.008	0.012	0.0006	yes	NA
2	1	0.021	-0.012	0.0010	yes	NA
2	2	0.030	0.006	0.0013	yes	NA
2	3	0.021	-0.007	0.0010	yes	NA
3	1	0.013	-0.030	0.0016	no	NA
3	2	0.008	0.052	0.0006	no	NA
3	3	0.005	0.003	0.0002	yes	NA

Note: NA = not applicable.

Specific Gravity

The following comments may be made about the specific gravity results given in Table 11 and Figure 11:

- The initial specific gravities of all samples were comparable, ranging from 1.25 to 1.33.
- All samples at all sites exhibited an increase in specific gravity over time. With the exception of Sample 3 at Site 2, the slopes of the regression lines were statistically different from zero.
- The estimated percent changes for the ballasted Samples 1 and 3 at Site 1 were about twice that for these two unballasted samples at Sites 2 and 3.
- In the case of Sample 2, the estimated percent change for the ballasted material at Site 1 was essentially the same as that for the unballasted materials at Sites 2 and 3.

Water Vapor Transmission

The following comments may be made about the water vapor transmission (WVT) results given in Table 12 and Figure 12:

- Most samples displayed decreases in WVT over time. However, only three (Sample 1 at Sites 1 and 3 and Sample 2 at Site 1) had regression lines with slopes statistically different from zero.

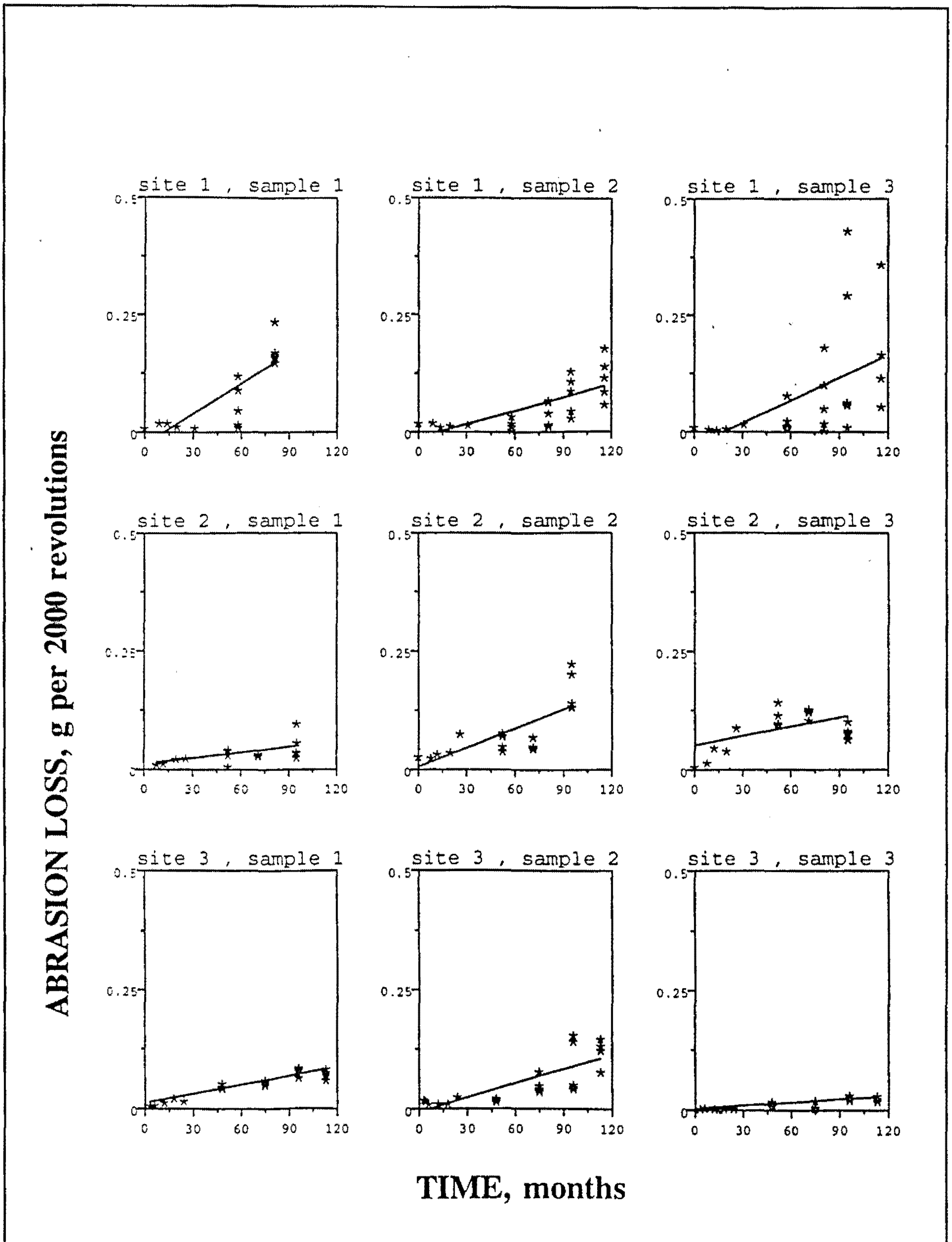

Figure 9. Results of the abrasion loss tests.

Table 10. Summary of thickness results (ASTM D 1593 or D 751).

Sample No.	Site No.	M_i (in.)	A_0 (in.)	$A_1 \times 10^{-6}$	Stat. Sign.	Est. Change in 100 Months (%)
1	1	0.046	0.046	-71	yes	-15 ± 1
1	2	0.050	0.050	-25	yes	-5 ± 1
1	3	0.049	0.049	-3	no	<-1 ± 3
2	1	0.047	0.047	-60	yes	-13 ± 1
2	2	0.047	0.048	-52	yes	-11 ± 1
2	3	0.047	0.047	-48	yes	-10 ± 1
3	1	0.047	0.047	-84	yes	-18 ± 1
3	2	0.055	0.054	-60	yes	-11 ± 3
3	3	0.048	0.050	-33	yes	-7 ± 2

- In most cases where the slope was not statistically different from zero, considerable scatter in the data occurred.
- For Samples 1 and 2, the WVT was considerably greater at Site 1 (ballasted installation) than at the other two sites.
- For Sample 3, the ordering is unclear due to the large uncertainties in the estimated changes at Sites 1 and 3.

Water Absorption

The following comments may be made about the water absorption results given in Table 13 and Figure 13:

- In six cases (exceptions for Sample 1 at Site 3 and Sample 2 at Sites 2 and 3), the slopes of the regression lines were not statistically different from zero. For the six cases, no statistically significant change in water absorption occurred over time. In these cases, little scatter in the data was observed. (The large uncertainties in the estimated percent change given in Table 13 result from the small initial values measured for water absorption.)
- In contrast to the six samples that showed no change of water absorption, for Sample 1 at Site 3 and Sample 2 at Sites 2 and 3, the slopes of the regression lines were positive and statistically different from zero. The estimated percent increases over time for these samples was 65, 108, and 165 percent, respectively.

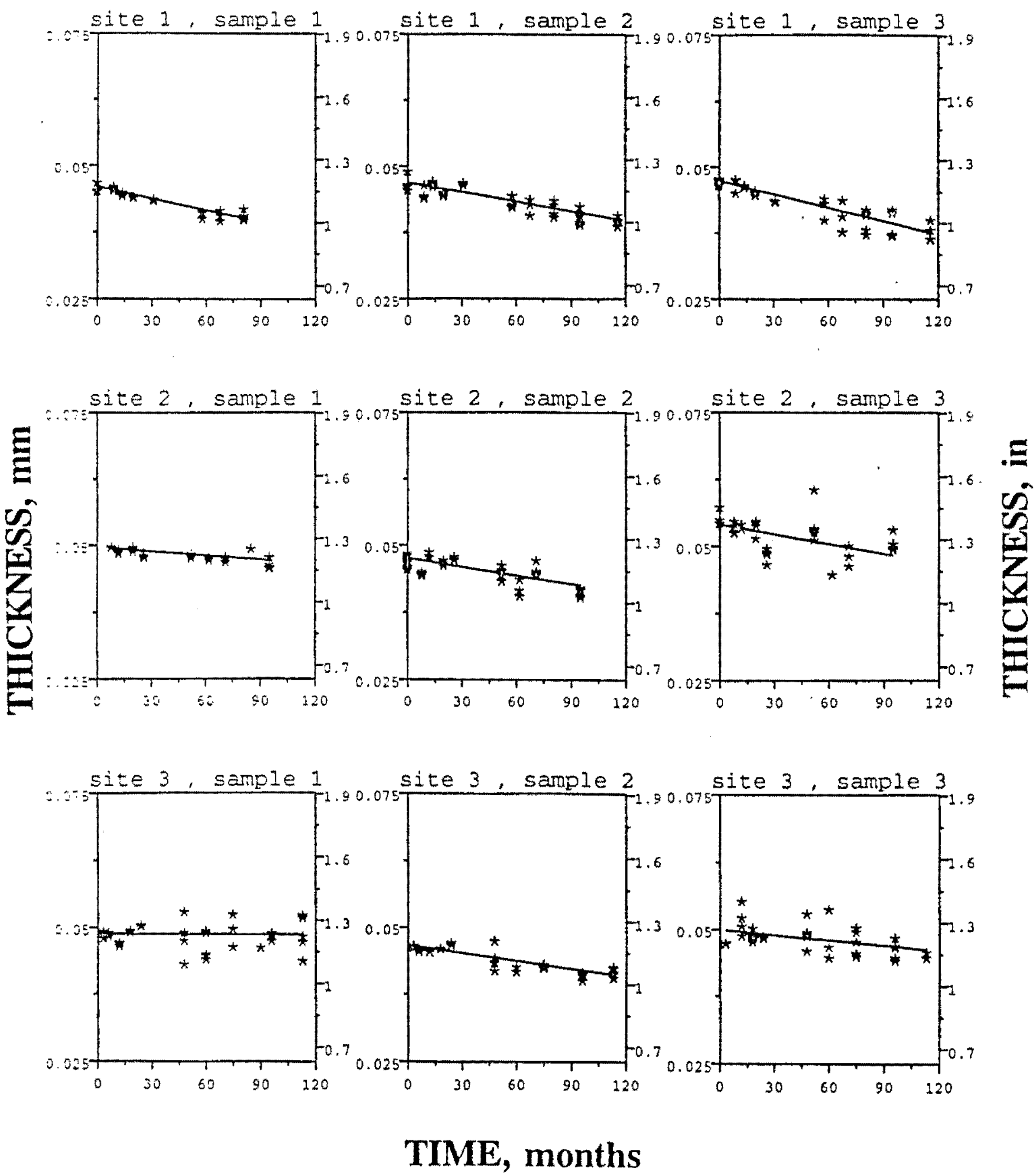

Figure 10. Results of the thickness tests.

Table 11. Summary of specific gravity results (ASTM D 792).

Sample No.	Site No.	M_i (sp gr)	A_0 (sp gr)	A_1	Stat. Sign.	Est. Change in 100 Months (%)
1	1	1.27	1.26	0.0009	yes	7 ± 0.8
1	2	1.28	1.27	0.0004	yes	3 ± 0.5
1	3	1.27	1.26	0.0004	yes	3 ± 0.6
2	1	1.27	1.26	0.0007	yes	6 ± 0.4
2	2	1.33	1.32	0.0007	yes	6 ± 0.6
2	3	1.32	1.31	0.0007	yes	5 ± 0.5
3	1	1.25	1.24	0.0008	yes	6 ± 1
3	2	1.26	1.26	0.0003	no	3 ± 1
3	3	1.28	1.26	0.0004	yes	3 ± 0.5

Dimensional Stability

The following comments may be made about the dimensional stability results given in Table 14 and Figure 14:

- For many cases (e.g., Sample 1 at Sites 2 and 3, and Sample 3 at all three sites), the dimensional stability (i.e., change in linear dimensions of specimens heated in the laboratory) of the samples did not change over time. In these instances, the slopes of the regression lines were not statistically different from zero, and little scatter was present in the data. (The large uncertainties in the estimated percent change given in Table 14 result from the small initial values measured for dimensional stability.)
- Only Sample 2 at Site 1 showed slopes that were statistically different from zero for both transverse and longitudinal directions. These slopes were negative, indicating less dimensional stability with time.
- Only Sample 2 showed slopes statistically different from zero for one direction (i.e., transverse) at all three sites.
- The results for the ballasted roofs at Site 1 were not consistent among the three samples. The negative slopes of the regression lines for Sample 2 were statistically different from zero in both directions; they were not statistically different from zero in either direction in the case of Sample 3; one slope (transverse) was and one slope (longitudinal) was not statistically different from zero in the case of Sample 1.

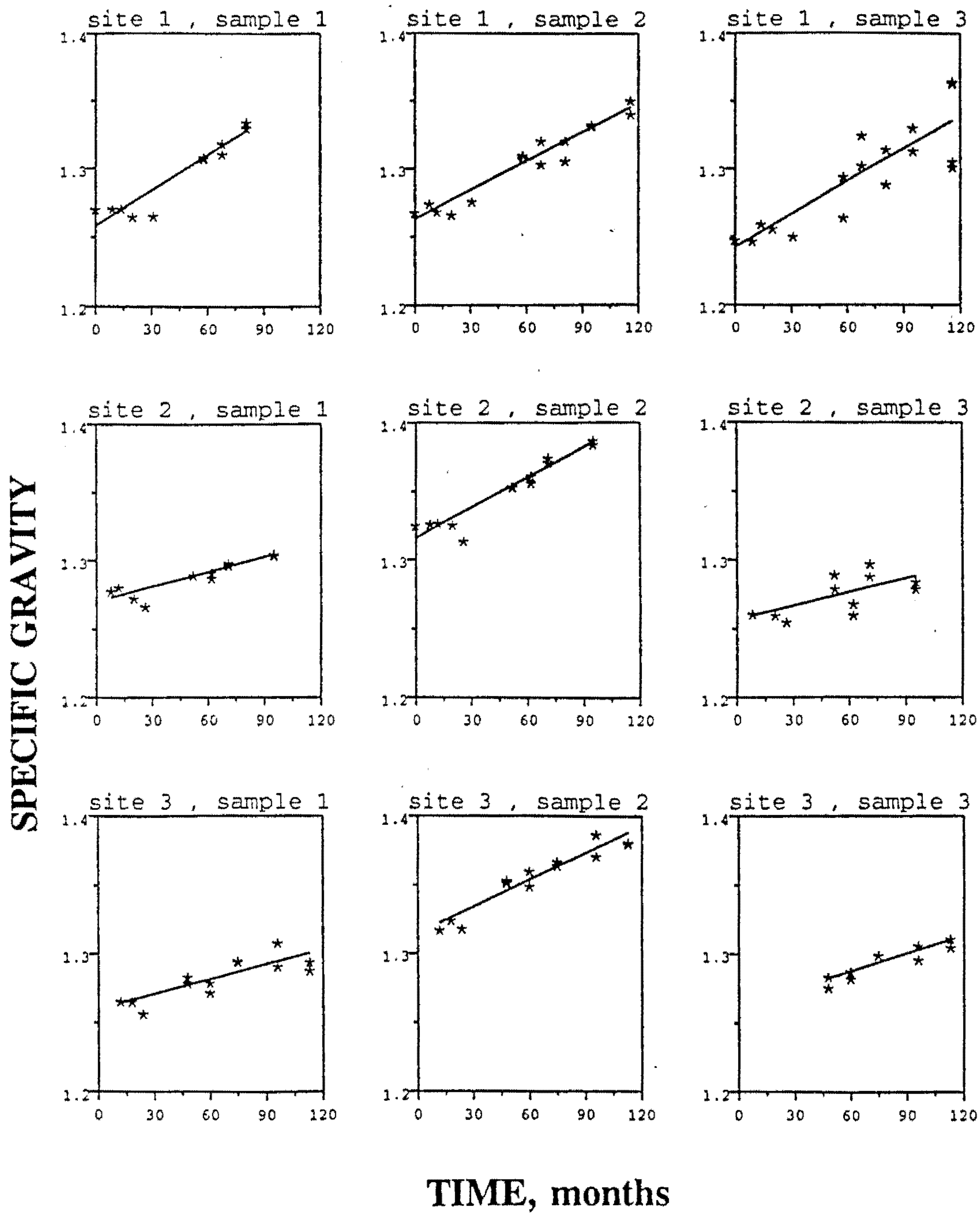

Figure 11. Results of the specific gravity tests.

Table 12. Summary of WVT results (ASTM E 96).

Sample No.	Site No.	M_i (perm)	A_0 (perm)	A_1	Stat. Sign.	Est. Change in 100 Months (%)
1	1	0.23	0.24	-0.0018	yes	-74 ± 12
1	2	0.23	0.21	-0.0005	no	-22 ± 11
1	3	0.27	0.25	-0.0006	yes	-25 ± 10
2	1	0.24	0.24	-0.0009	yes	-39 ± 10
2	2	0.26	0.25	-0.00004	no	-2 ± 12
2	3	0.27	0.22	0.0002	no	8 ± 16
3	1	0.24	0.23	-0.0003	no	-15 ± 20
3	2	0.23	0.24	-0.00003	no	1 ± 7
3	3	0.25	0.25	-0.0006	no	-25 ± 11

Seam Shear Strength

The following comments may be made about the seam shear strength results given in Table 15 and Figure 15:

- The initial shear strengths of the Type III reinforced membranes (Sample 1 at Sites 2 and 3 [see Table 1]) were greater than those of the Type I (Sample 1 at Site 1, and Sample 2 at all sites) and Type II (Sample 3 at all sites) membranes.
- The initial shear strengths of the solvent-welded seams, Samples 1 and 2 at Site 3 (Table 1), were comparable to those of the heat-welded seams (i.e., all other samples).
- The majority of the seam shear strengths increased over time. For these materials, the positive slopes of the regression lines were statistically different from zero. The range of estimated percent change was 7 to 35 percent.
- The solvent-welded seams, Samples 1 and 2 at Site 3, showed increases in strength of 30 and 7 percent, respectively. These values essentially bracketed those of the heat-welded seam samples (i.e., all other samples).
- The estimated percent increases in seam shear strength for the ballasted membranes at Site 1 were found at the high end of the range, with values from 26 to 35 percent.
- Samples 2 and 3 at Site 2 experienced no statistically significant change in seam shear strength with time.

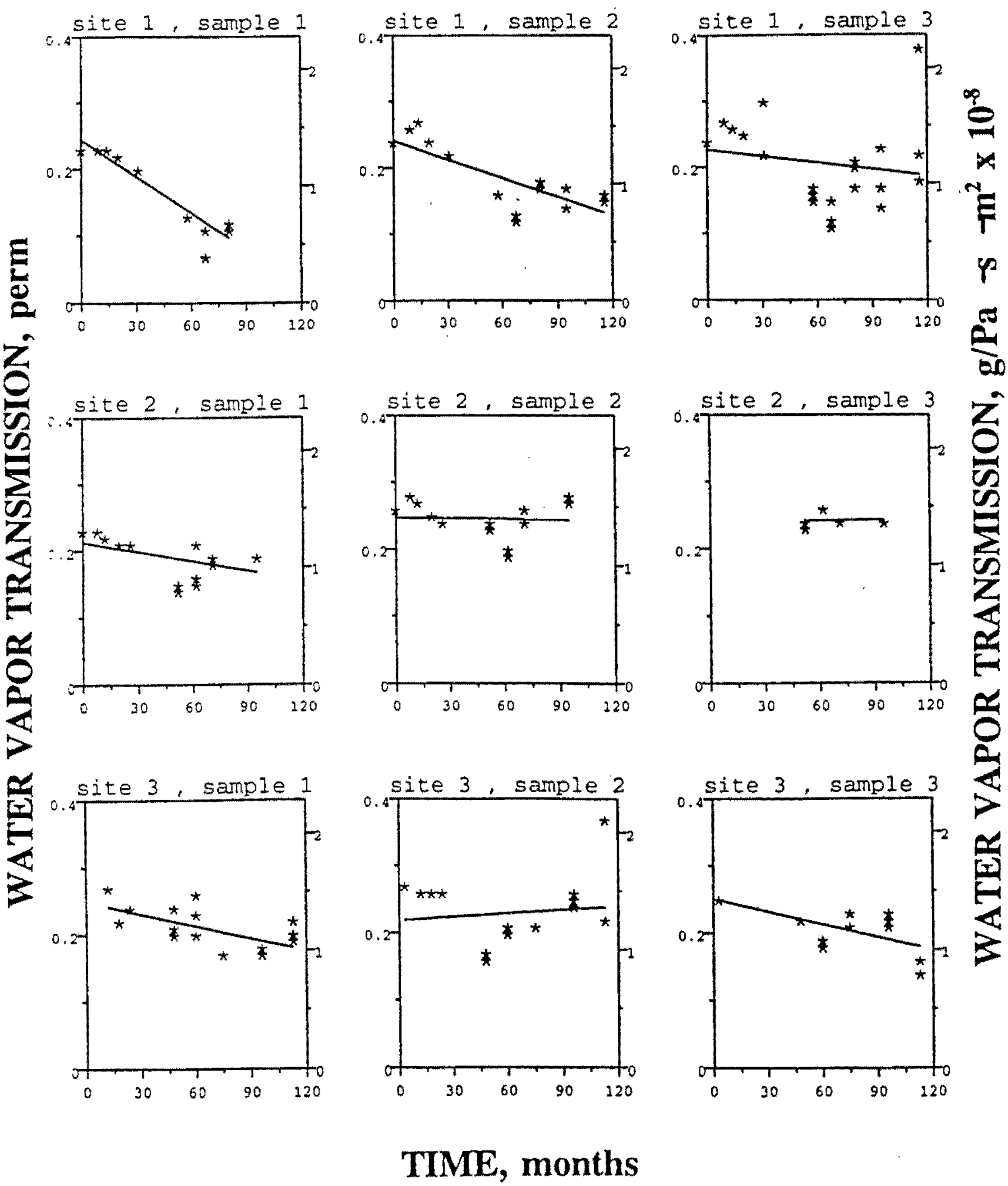

Figure 12. Results of the water vapor transmission tests.

Table 13. Summary of water absorption results (ASTM D 570).

Sample No.	Site No.	M_i (% mass)	A_0 (% mass)	A_1	Stat. Sign.	Est. Change in 100 Months (%)
1	1	0.2	0.40	0.0009	no	23 ± 94
1	2	3.3	3.8	-0.0037	no	-10 ± 16
1	3	2.6	2.9	0.0189	yes	65 ± 19
2	1	2.2	1.9	-0.0070	no	-36 ± 15
2	2	7.0	4.4	0.0477	yes	108 ± 20
2	3	1.6	2.0	0.0324	yes	165 ± 38
3	1	0.8	0.8	0.0015	no	18 ± 25
3	2	2.3	2.0	0.0038	no	19 ± 32
3	3	1.0	1.2	0.0046	no	40 ± 35

Seam Peel Strength

During testing of the membrane specimens, the peel test was found to be difficult to conduct on the specimens taken from roofs. The difficulty involved creating "flaps" on the test specimens, either by partial delamination of the seam or addition of a PVC strip on the seam to hold the specimens in the grips of the testing machine.

The following comments may be made about the seam peel strength results given in Table 16 and Figure 16:

- None of the changes in seam peel strength had regression lines with slopes statistically different from zero. Considerable scatter was evident in the data in all cases. The scatter may be associated with the difficulties encountered in performing the peel tests.
- Important differences between the peel strengths of seams of the various samples may have been expected only if the bonding processes during membrane installation had been inadequate. This was unlikely in this study as all seams performed satisfactorily over the service lives of the membrane samples.

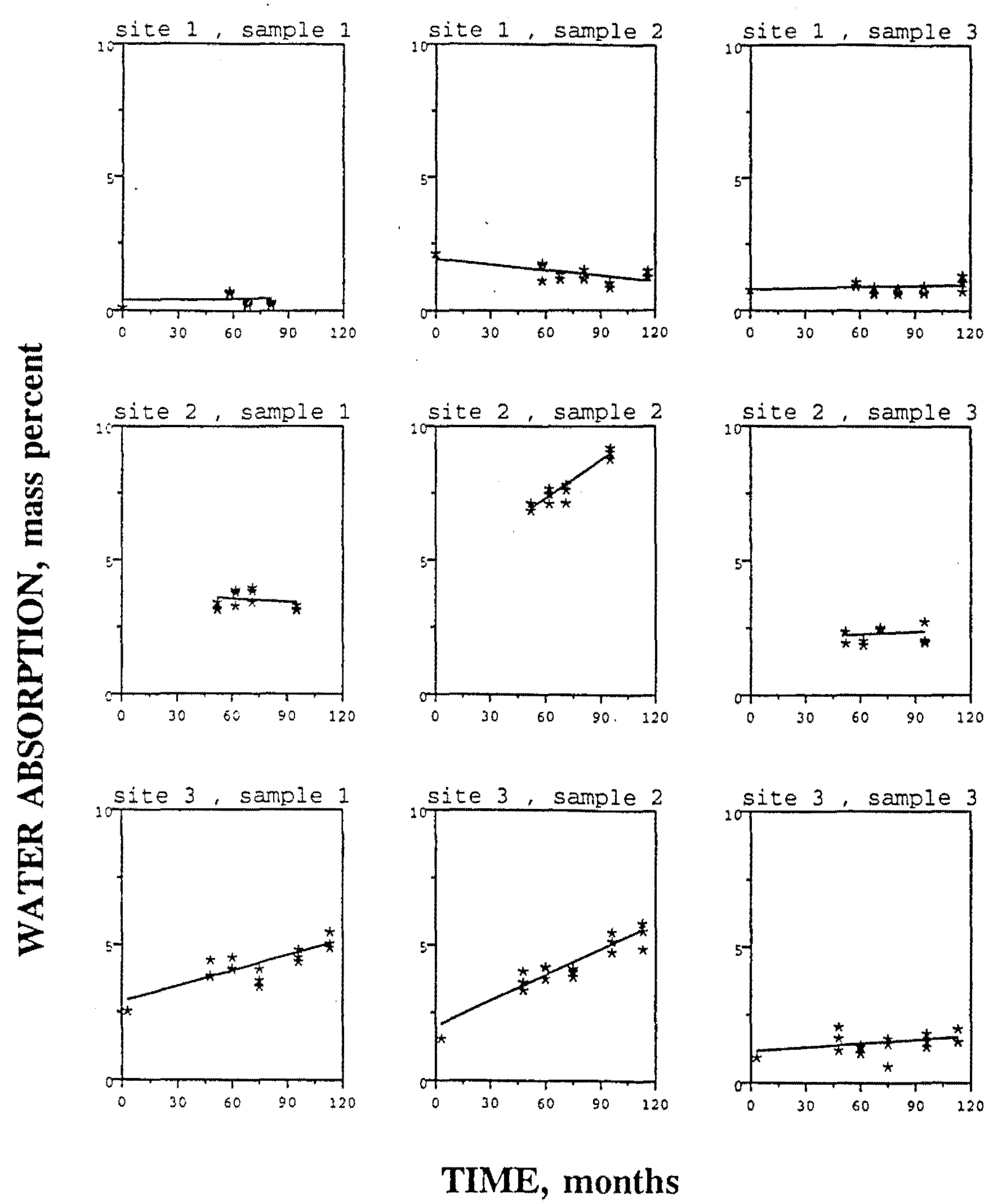

Figure 13. Results of the water absorption tests.

Table 14. Summary of dimensional stability results (ASTM D 1204).

Sample No.	Site No.	Sheet Dir.	M_i (%)	A_0 (%)	A_1	Stat. Sign.	Est. Change in 100 Months (%)
1	1	trans.	0.88	1.14	-0.0478	yes	-421 ± 295
		long.	-2.39	-2.32	-0.0203	no	-88 ± 55
1	2	trans.	0.0	0.12	-0.0028	no	-238 ± 524
		long.	-0.38	-0.23	-0.00003	no	-1 ± 68
1	3	trans.	0.0	0.09	-0.0026	no	-299 ± 416
		long.	-0.38	-0.18	-0.0017	no	-94 ± 154
2	1	trans.	0.88	1.73	-0.0555	yes	-320 ± 182
		long.	-0.29	-2.36	-0.0181	yes	-76 ± 43
2	2	trans.	0.75	0.80	-0.0176	yes	-219 ± 94
		long.	-1.77	-1.75	-0.0026	no	-15 ± 43
2	3	trans.	1.0	0.68	-0.0177	yes	-259 ± 181
		long.	-2.13	-1.89	-0.0074	no	-39 ± 32
3	1	trans.	0.0	0.03	-0.0011	no	-405 ± 2090
		long.	-0.13	-0.06	-0.0030	no	-500 ± 1560
3	2	trans.	0.62	0.54	-0.0081	yes	-150 ± 47
		long.	-0.26	-0.21	-0.0011	no	-54 ± 78
3	3	trans.	0.13	0.13	-0.0016	no	-121 ± 174
		long.	-0.13	0.09	-0.0004	no	-49 ± 130

Note: trans. = the transverse direction of the sheet; long. = longitudinal direction of the sheet.

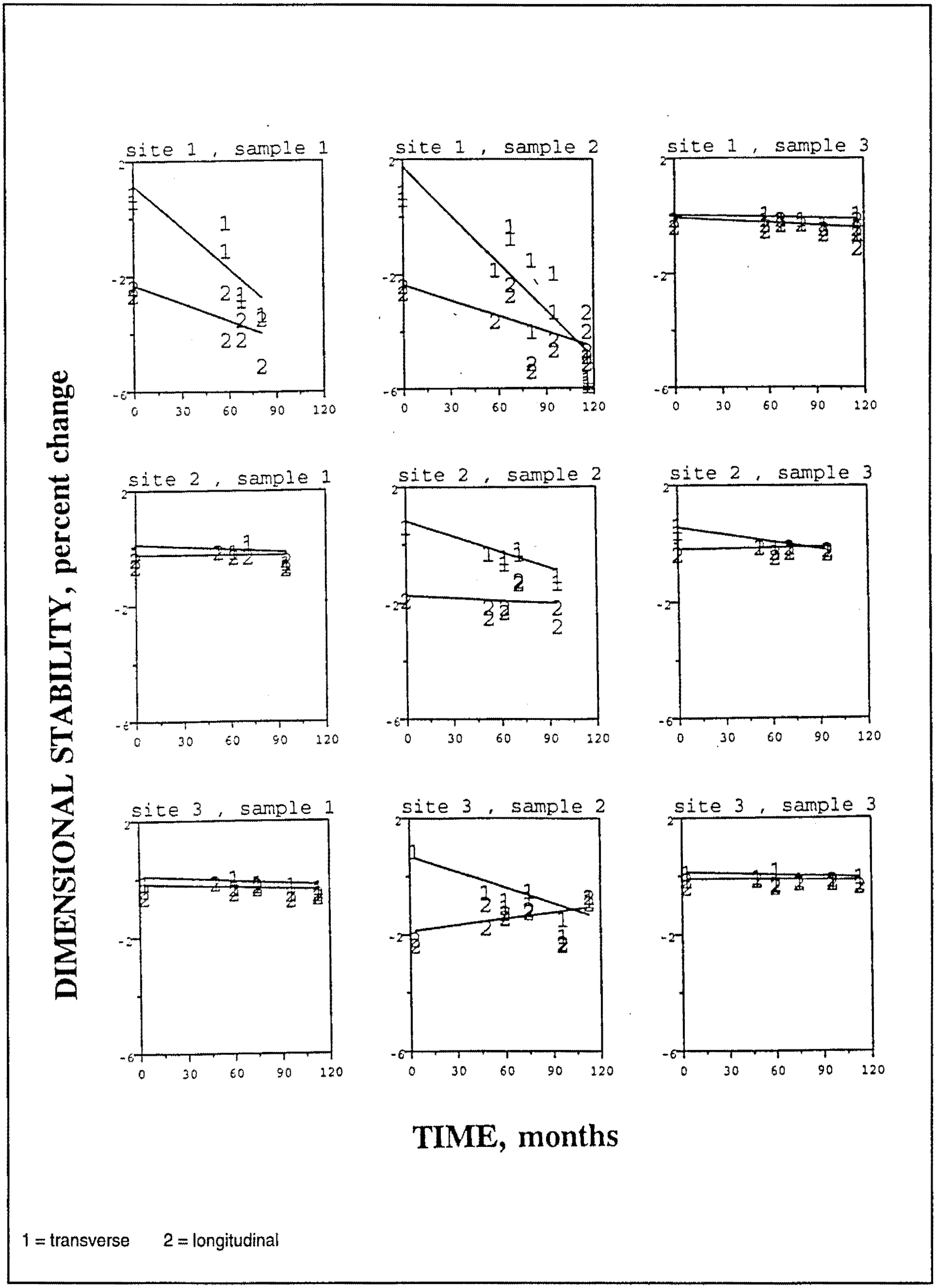

Figure 14. Results of the dimensional stability tests.

Table 15. Summary of seam shear strength results (ASTM D 882).

Sample No.	Site No.	M_i (lbf/in)	A_0 (lbf/in)	A_1	Stat. Sign.	Est. Change in 100 Months (%)
1	1	79.3	82.1	0.29	yes	35 ± 4
1	2	149.2	156.0	0.31	yes	20 ± 3
1	3	116.3	130.2	0.39	yes	30 ± 8
2	1	76.2	75.4	0.20	yes	26 ± 4
2	2	82.3	81.1	0.004	no	0.5 ± 3
2	3	79.8	80.4	0.06	yes	7 ± 2
3	1	76.1	74.5	0.22	yes	30 ± 3
3	2	74.0	66.8	0.03	no	5 ± 6
3	3	77.0	75.6	0.08	yes	11 ± 2

Table 16. Summary of seam peel strength results (ASTM D 1876).

Sample No.	Site No.	M_i (lbf/in.)	A_0 (lbf/in.)	A_1	Stat. Sign.	Est. Change in 100 Months (%)
1	1	44.4	35.0	0.134	no	38 ± 21
1	2	40.6	34.2	-0.061	no	-18 ± 13
1	3	19.8	22.3	0.039	no	17 ± 3
2	1	25.6	28.4	0.054	no	19 ± 14
2	2	13.7	13.9	-0.005	no	-4 ± 16
2	3	13.5	12.3	0.042	no	34 ± 14
3	1	35.5	37.2	0.046	no	12 ± 10
3	2	25.2	18.3	0.068	no	37 ± 41
3	3	50.8	44.2	-0.050	no	-11 ± 14

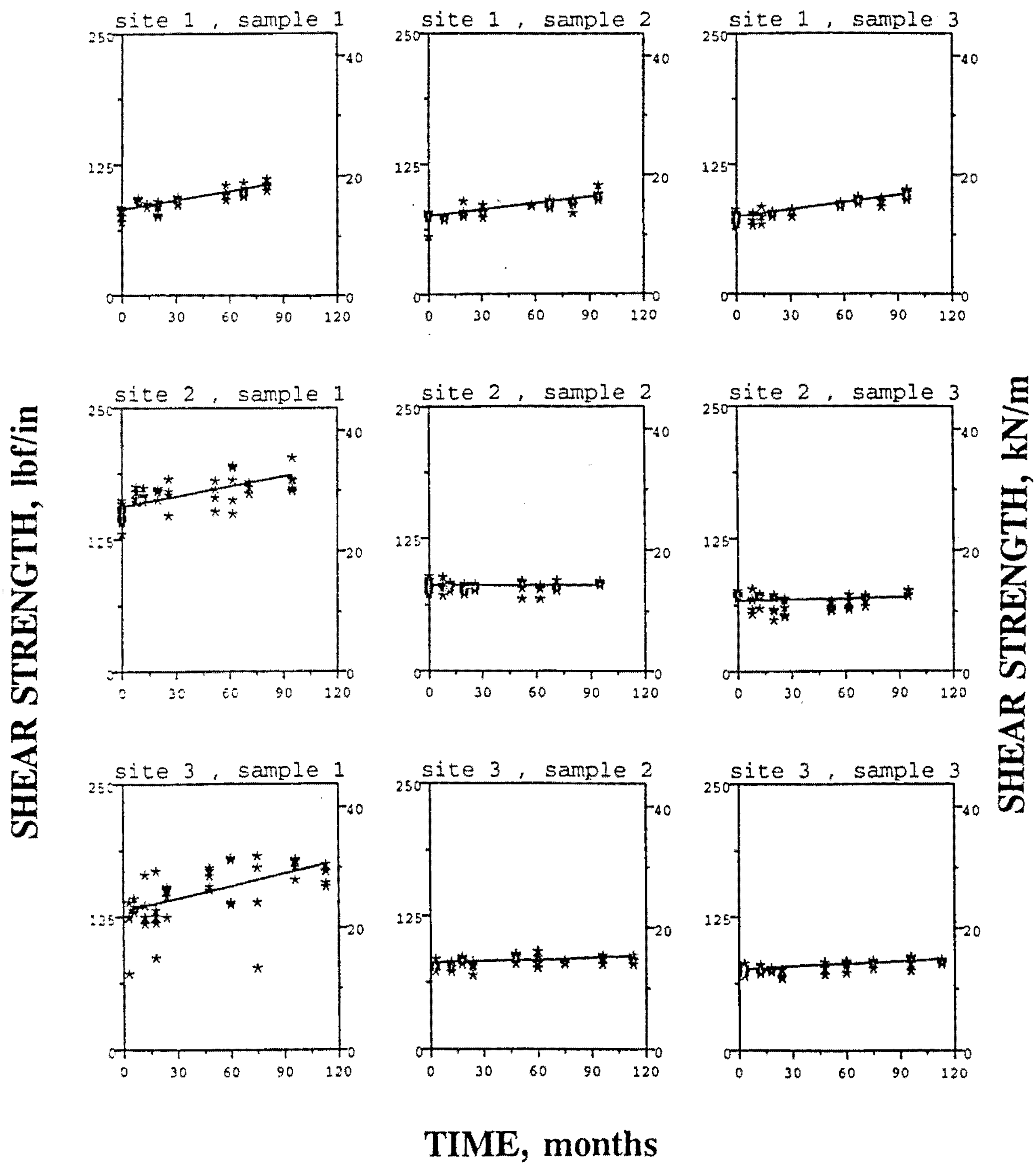

Figure 15. Results of the seam shear strength tests.

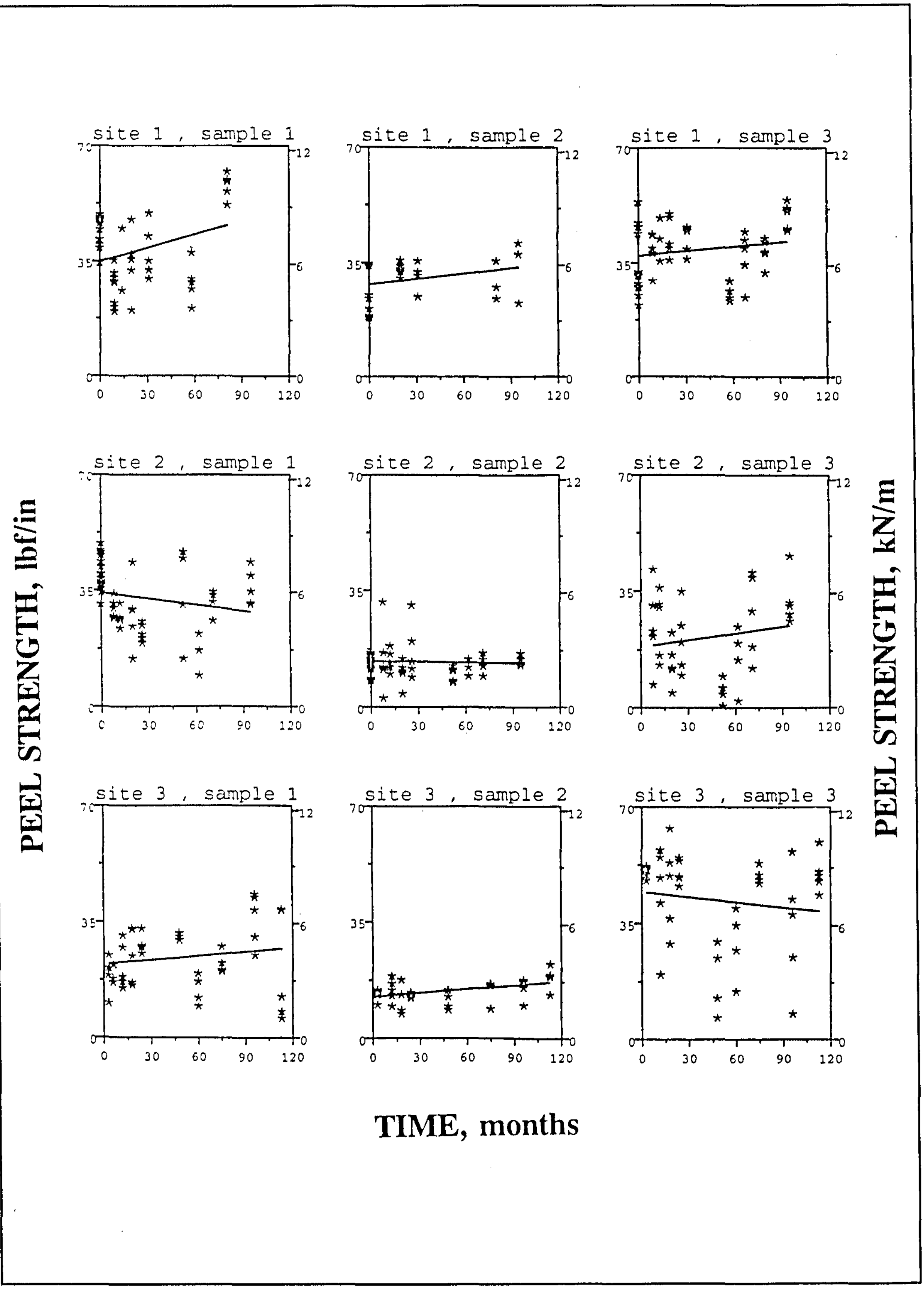

Figure 16. Results of the seam peel strength tests.

5 Conclusions and Commentary

Conclusions

The intent of the 10-year field exposure study of the performance of PVC roofing membrane materials installed at Chanute Air Force Base, IL, Dugway Proving Ground, UT, and Fort Polk, LA was to compare the results of laboratory tests of membrane properties with the observations noted on field performance. Periodically over the 10 years, USACERL obtained samples from the roofs for laboratory characterization of selected mechanical and physical properties. Additionally, the roofs were visually inspected to evaluate their performance. The performance was generally satisfactory at Dugway and Fort Polk, but problems relating to membrane shattering and splitting occurred at Chanute. A major difference in the roof construction at Chanute was that the membranes were ballasted; at Dugway and Fort Polk, they were mechanically attached or fully adhered. Experience with the performance of PVC roofing has shown that ballasted systems may have an elevated risk of poor performance.

Because of the less-than-satisfactory performance at Chanute, statistical analysis of the 10-year PVC data set focused on whether changes in any of the measured properties were consistently different for samples from Chanute than for samples from Dugway and Fort Polk. The properties measured during the study were: plasticizer content, plasticizer loss, tensile strength, elongation, tear strength, ply adhesion, abrasion loss, thickness, specific gravity, water vapor transmission, water absorption, dimensional stability, seam shear strength, and seam peel strength.

The results of the analyses indicated that most of the measurements did not discriminate between the performance of the PVC membranes at Chanute and those at Dugway and Fort Polk. This indiscriminate performance may be because a field experiment has hidden variables that are difficult to control and may have significant influence on the test results (i.e., the variability of membrane materials installed in large quantities at different locations and times).

As an illustration of the nondiscriminating nature of the results, it was observed that, as may have been expected, all samples at the three sites lost plasticizer during the exposure period. Two of the three samples from Chanute did not lose significantly more plasticizer than those from Dugway or Fort Polk. The limited data on plasticizer content showed that the aged membrane sample that eventually shattered at Chanute had the lowest average content. However, these data also indicated that, with the exception of the shattered membrane at Chanute, aged Sample 1 that performed well at Fort Polk had, on the average, equal or less plasticizer than any of the other samples at the other sites. Also, the plasticizer loss test gave mixed results. While the tests implied that aged membrane Samples 1 and 2 had less plasticizer at Chanute than at Dugway and Fort Polk, tests of the aged membrane Sample 3 suggested that samples from the three sites had about the same amount.

Only in the case of tear strength and thickness were the changes larger for the ballasted membranes at Chanute than for the nonballasted membranes at Dugway and Fort Polk. In general for all samples, tear strength increased with exposure time, whereas the thickness decreased with time. It is questioned whether loss of plasticizer would cause embrittlement of the PVC material which, in turn, would increase tear resistance. Similarly, plasticizer loss could shrink the membrane and be displayed as a loss in thickness. Both possibilities would need to be investigated in the laboratory to reach a definitive conclusion.

For a number of other tests, the results showed that changes in the measured property were greater for two, but not all three, of the ballasted membranes at Chanute than for the nonballasted membranes at Dugway and Fort Polk. Included here were tensile strength, specific gravity, and water vapor transmission. Tests that showed no distinction between the ballasted Chanute membranes and the nonballasted membranes were elongation, abrasion loss, water absorption, and dimensional stability.

Finally, the shear and peel tests on the seams did not detect differences between heat-welded and solvent-welded seams. This finding may have been expected, as both types of seams performed satisfactorily over the duration of the study. This would imply that, for the test roofs, the two seam fabrication techniques provided acceptable bonds. The initial shear strengths for both types of seams were comparable, and generally increased with exposure time. Seam peel strengths had considerable data scatter and differences were not statistically significant.

Final Comment

Note that the data, analyses, and other information in this report are for PVC membrane materials manufactured over a decade ago. Changes in PVC roofing membrane technology have occurred since that time, as evidenced by the proposed revisions to ASTM Standard Specification D 4434. Because of changing technology, readers are cautioned against broadening the interpretation of the results of this study to current PVC membrane materials without supporting data to do so.

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Appendix: Variability in the Descriptors for the Measured Properties

This appendix presents tables summarizing the variability in the descriptors M_i, A_0, and A_1 used in the analysis of the data for the PVC membrane materials. A table is given for each property (with the exception of plasticizer content) and each corresponds to a table of data presented in the main body of this report. In each table, the range of relative standard deviation covers the three samples at the three exposure locations.

Table A1. Variability of the descriptors for the plasticizer loss results.

Descriptors	Relative Standard Deviation
M_i initially measured average property value	Range: 6 to 20%
A_0 estimate of the true value at initial time	Range: 6 to 25%
A_1 the slope of the line fitted to the data	Ranged from 10 to 100% with the exception of Sample 1 at Site 2 and Sample 3 at Site 2, which were 155 and 529%, respectively.

Note: This table corresponds to Table 4 in the main text.

Table A2. Variability of the descriptors for the tensile strength results.

Descriptors	Relative Standard Deviation
M_i initially measured average property value	Range: 1.3 to 6.5%
A_0 estimate of the true value at initial time	Range: 1 to 4%
A_1 the slope of the line fitted to the data	Ranged from 8 to 36%, with the exception of Sample 2 at Site 3, which was 157%.

Note: This table corresponds to Table 5 in the main text.

Table A3. Variability of the descriptors for the elongation results.

Descriptors	Relative Standard Deviation
M_i initially measured average property value	Ranged from 8 to 15% with the exception of Sample 1 at Site 1, which was 38%.
A_0 estimate of the true value at initial time	Range: 1 to 4%
A_1 the slope of the line fitted to the data	Range: 13 to 40%

Note: This table corresponds to Table 6 in the main text.

Table A4. Variability of the descriptors for the tear strength results.

Descriptors	Relative Standard Deviation
M_i initially measured average property value	Range: 5 to 11%
A_0 estimate of the true value at initial time	Range: 2 to 3%
A_1 the slope of the line fitted to the data	Ranged from 6 to 22% with the exception of Samples 2 and 3 at Site 2, which were 85 and 55%, respectively.

Note: This table corresponds to Table 7 in the main text.

Table A5. Variability of the descriptors for the ply-adhesion results.

Descriptors	Relative Standard Deviation
M_i initially measured average property value	Sample 1 at Sites 2 and 3 were 11 and 4%, respectively.
A_0 estimate of the true value at initial time	Sample 1 at Sites 2 and 3 were 8 and 13%, respectively.
A_1 the slope of the line fitted to the data	Sample 1 at Sites 2 and 3 were 107 and 13%, respectively.

Note: This table corresponds to Table 8 in the main text.

Table A6. Variability of the descriptors for the abrasion loss results.

Descriptors	Relative Standard Deviation
M_i initially measured average property value	Only one initial measurement of each sample at each site was made; consequently, no relative standard deviation is given.
A_0 estimate of the true value at initial time	Ranged from 8 to 100% with the exception of Sample 2 at Sites 2 and 3 and Sample 3 at Site 1, which were 327, 178, and 158%, respectively.
A_1 the slope of the line fitted to the data	Range: 7 to 38%

Note: This table corresponds to Table 9 in the main text.

Table A7. Variability of the descriptors for the thickness results.

Descriptors	Relative Standard Deviation
M_i initially measured average property value	Range: 0.2 to 3.4 %
A_0 estimate of the true value at initial time	Range: 0.3 to 1.6 %
A_1 the slope of the line fitted to the data	Ranged from 5 to 28%, with the exception of Sample 1 at Site 3, which was 293%.

Note: This table corresponds to Table 10 in the main text.

Table A8. Variability of the descriptors for the specific gravity results.

Descriptors	Relative Standard Deviation
M_i initially measured average property value	Only one initial measurement of each sample at each site was made; consequently, no relative standard deviation is given.
A_0 estimate of the true value at initial time	Range: 0.2 to 0.4%
A_1 the slope of the line fitted to the data	Ranged from 7 to 20% with the exception of Sample 3 at Site 2, which was 39%.

Note: This table corresponds to Table 11 in the main text.

Table A9. Variability of the descriptors for the water vapor transmission results.

Descriptors	Relative Standard Deviation
M_i initially measured average property value	With the exception of Sample 3 at Site 2, only one initial measurement of each sample at each site was made; consequently, no relative standard deviation is given. The relative standard deviation for Sample 3 at Site 2 was 2.5%.
A_0 estimate of the true value at initial time	Range: 5 to 13%
A_1 the slope of the line fitted to the data	Range: 11 to 714%

Note: This table corresponds to Table 12 in the main text.

Table A10. Variability of the descriptors for the water absorption results.

Descriptors	Relative Standard Deviation
M_i initially measured average property value	Only one initial measurement of each sample at Sites 1 and 3 was made; consequently, no relative standard deviation is given for these samples. The relative standard deviation for the three samples at Site 2 was 4, 2, and 11%, respectively.
A_0 estimate of the true value at initial time	Range: 10 to 55%
A_1 the slope of the line fitted to the data	Ranged from 10 to 156% with the exception of Sample 1 at Site 1, which was 355%.

Note: This table corresponds to Table 13 in the main text.

Table A11. Variability of the descriptors for the dimensional stability results for the transverse direction.

Descriptors	Relative Standard Deviation
M_i initially measured average property value	Only two initial measurements for each sample at each site were made; the relative standard deviation ranged from 0 to 27% with the exception of Sample 3 at Site 3, which was 141%.
A_0 estimate of the true value at initial time	Ranged from 4 to 50 with the exception of Sample 1 at Sites 2 and 3 and Sample 3 at Site 1, which were 133, 96, and 400%, respectively.
A_1 the slope of the line fitted to the data	Range: 16 to 116%

Note: This table corresponds to Table 14 in the main text.

Table A12. Variability of the descriptors for the dimensional stability results for the longitudinal direction.

Descriptors	Relative Standard Deviation
M_I initially measured average property value	Only two initial measurements for each sample at each site were made; the relative standard deviation ranged from 3 to 47% with the exception of Sample 3 at Sites 1 and 3, which was 141%.
A_0 estimate of the true value at initial time	Ranged from 22 to 70% with the exception of Sample 3 at Site 1, which was 253%.
A_1 the slope of the line fitted to the data	Ranged from 33 to 107% with the exception of Sample 1 at Site 2, Sample 2 at Site 2, and Sample 3 at Site 3, which were 6770, 259, and 194%, respectively.

Note: This table corresponds to Table 14 in the main text.

Table A13. Variability of the descriptors for the seam shear strength results.

Descriptors	Relative Standard Deviation
M_I initially measured average property value	Range: 4 to 25%
A_0 estimate of the true value at initial time	Range: 1 to 4%
A_1 the slope of the line fitted to the data	Ranged from 12 to 39% with the exception of Sample 2 at Site 2 and Sample 3 at Site 2, which were 500 and 114%, respectively.

Note: This table corresponds to Table 15 in the main text.

Table A14. Variability of the descriptors for the seam peel strength results.

Descriptors	Relative Standard Deviation
M_I initially measured average property value	Range: 3 to 50%
A_0 estimate of the true value at initial time	Range: 5 to 18%
A_1 the slope of the line fitted to the data	Ranged from 9 to 120% with the exception of Sample 2 at Site 2, which was 392%.

Note: This table corresponds to Table 16 in the main text.

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