PERFORMANCE OF TAPE-BONDED SEAMS OF EPDM MEMBRANES: INITIAL CHARACTERIZATION

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A joint industry-government study has been established to develop a test protocol based on creep testing and criteria for evaluating performance of tape-bonded seams in EPDM (ethylene-propylene-diene terpolymer) roofing membranes. This study focuses on the creep-response of peel specimens subjected to varying loads and prepared under a variety of conditions. Before conducting the creep experiments, it was necessary to assure that the strength of the specimens had stabilized. This paper presents the results of the laboratory investigations to characterize peel strength. The experimentation was performed on samples prepared using two commercial tape systems (i.e., tape and primer combinations). The initial peel strength of tape-bonded specimens was determined as a function of elapsed time after application, application pressure, duration of applied pressure, and surface condition of the EPDM rubber. Peel strength increased over a relatively short time after sample preparation. It was concluded that a waiting period of three weeks was adequate to assure that strength had stabilized. Additionally, peel strength was unaffected by either the pressure applied or the duration of applied pressure, and was adversely affected (i.e., it decreased) when the EPDM surface was not adequately cleaned or primed. In addition to the measurements of laboratory-prepared samples, peel strengths were determined for nine tape-bonded seam samples removed from satisfactorily performing roofs having ages of 0.5 to 6.5 years. The strengths were both higher and lower than the strengths measured for laboratory specimens prepared with cleaned, primed EPDM. The results for laboratory- and field-prepared seams emphasize the need to follow instructions for proper surface preparation during the fabrication of tape-bonded seams.

KEYWORDS

Building technology, EPDM, liquid-adhesive-bonding, peel strength, pressure, single-ply roofing, seam characterization, seams, tape-bonding and time.

INTRODUCTION

Background

In the United States, EPDM (ethylene-propylene-diene terpolymer) rubber membranes have been used in low-sloped roofing applications for approximately 20 years. EPDM possesses good weathering resistance due to its chemical inertness, and the performance of EPDM roofing has been satisfactory, although not problem-free. The chemically inert, non-polar nature of the rubber renders adhesive bonding of sheets during the formation of roofing membranes difficult. Over the years, the main source of problems reported for EPDM roofing has been the seams.[1]

Since EPDM's introduction as a roofing material, several types of seam bonding systems have been used. Chief among them are liquid (i.e., solvent-based) adhesives, based on either polychloroprene or butyl polymers, applied with or without primer.[2,3] Although not employed extensively, some pre-formed tape adhesives have also been used over the years. The history of tape systems for bonding EPDM roofing membrane materials has been reviewed by Dupuis.[4] In recent years, an increase in the use of tape systems has occurred, and the trend is expected to continue in the future. Hatgas and Spector[5] have listed reasons contributing to the increased use including:

- reduction in the amount of volatile organic compounds (VOCs) released during seam fabrication as the tapes are 100 percent solids (i.e., solvent-free);
- ease of application and decreased time taken to fabricate seams; and
- the availability of an adhesive system that has uniform width and thickness so that the prescribed amount of adhesive is applied during installation.

Some of today's tape systems have been available for over a decade[4,5] and are expected to give satisfactory performance. Nevertheless, some roofing contractors and consultants have expressed concern that these tapes are being used in increased quantities without sufficient independent evaluation. Few reports or papers on tape-bonded seam performance are available in the technical literature.

Joint Industry-Government Research Project on Tape Seams

In response to the need to develop non-proprietary data on tape-seam performance, three EPDM membrane and two tape manufacturers along with two trade associations are undertaking a joint research project with the National Institute of Standards and Technology (NIST) through a Cooperative Research and Development Agreement (CRADA). The industrial CRADA members are Adco, Ashland, Carlisle Syntec, Firestone, Genflex, the National Roofing Contractors Association (NRCA), and the Roof Consultants Institute (RCI). The U.S. Army Construction Engineering Research Laboratories (CERL) is also a sponsor. The objective of the study is to compare the performance of tape-bonded and liquid-adhesive-bonded seams in

EPDM roofing membranes, and to develop a test protocol based on creep testing and recommended criteria for evaluating the performance of tape-bonded seams in EPDM roofing membranes. The experimental program will focus on subjecting tape-bonded seam specimens of EPDM membranes to creep testing, and will consist of three phases. The study design is definite for Phases I and II. Phase III will be considered for implementation near the end of Phase II. In brief, the following is planned:

- In Phase I, the creep-rupture response (time-to-failure) of tape-bonded seam specimens subjected to various peel loads under ambient conditions will be compared to that of liquid-adhesive-bonded specimens in a long-term creep-rupture experiment.
- In Phase II, the creep-rupture response of tape-bonded seams will be investigated under ambient conditions as a function of specimen-application variables such as the presence of primer, rubber surface cleanness, pressure, application temperature, and tape thickness.
- In Phase III, it is expected that the creep-rupture response of tape-bonded seams will be investigated as a function of test temperature and type of loading (i.e., peel versus shear).

Concurrent with the laboratory experimentation, field inspections of EPDM roofing systems having tape-bonded seams will be conducted and seam samples will be obtained. Mechanical properties of these field-seam specimens will be determined and compared with those of liquid-adhesive bonded seams removed from roofs in service in previous studies.

Past Research on EPDM Seam Performance

Considerable research on liquid-adhesive seams has been conducted by NIST using creep-rupture experiments to characterize the behavior of these seams when subjected to constant load over time.[6-13] Field experience has suggested that many seam defects result from the rheological (deformation/flow) behavior of the adhesive and not chemical deterioration.[8,13] In a creep-rupture experiment, a seam specimen of a fixed length is stressed under a constant load and the time over which it sustains the load until total separation is recorded. This time is called the time-to-failure. The objective of the creep-rupture experiments is to determine the sensitivity of seam time-to-failure under creep loading to various variables associated with seam formation and environmental exposure. Better performing seams are those having longer times-to-failure.

Purpose of this Paper

Before conducting the Phase I creep-rupture experiments on the tape-bonded seams, it was necessary to assure that their short-term strength had stabilized. This paper presents the results of laboratory experiments on initial strength characterization. The variables investigated were: elapsed time after fabrication, application pressure, duration of applied pressure, and surface condition of the EPDM rubber. Because the creep tests are to be conducted with the specimens loaded in a T-peel configuration, the short-term strength tests were T-peel. In practice, seam defects that develop often occur within the first three years of service. This observation implies that the cause may be associated with the rheological behavior of the adhesive which, in turn, is influenced by poor workmanship (e.g., inadequate cleaning and adhesive thickness).[7,13] Although in practice seams may be subjected to both peel and shear stresses, the large portion of the field-observed defects such as unbonded ripples and fishmouths are considered to be due to peel stresses. This is consistent with the results of our laboratory experimentation in which we have found that seam specimens under constant peel load undergo relatively-rapid delamination in comparison to specimens loaded in shear.[7,13]

In addition to presenting the results of the peel tests on laboratory-prepared specimens, the paper summarizes the observations of initial field inspections of roofs having tape-bonded seams and provides data on the peel strengths of seam samples removed from the roofs.

EXPERIMENTAL

This section of the paper summarizes the experimental protocol. The Appendix presents a more complete description. T-peel specimens were prepared in the laboratory using a commercially available EPDM sheet and one of two commercially available tape-bonding systems comprised of a tape and primer (designated Tape System 1 and Tape System 2). The surface of the EPDM rubber was well cleaned. Primer was then applied at a rate recommended by the tape system manufacturer using a drawdown blade technique. After evaporation of the primer solvent, the tape was applied to the rubber such that the direction of the roll was perpendicular to the length of the T-peel specimen. The specimen was placed in a press for 10 s at 0.69 MPa (100 lbf/in.^{2}). Strong[14] has reported that roofing mechanics exert a roller pressure of about 0.69 MPa (100 lbf/in.^{2}). It is for this reason that 0.69 MPa (100 lbf/in.^{2}) was selected for use as the control pressure in this and other NIST studies on EPDM seam performance. After pressing, the specimens were kept at ambient laboratory conditions, about 23°C (73°F) and 40-50 percent RH, until subjected to peel testing. Peel strength was determined at ambient laboratory conditions using a universal testing machine equipped with a computer and software for data collection and analysis.

RESULTS AND DISCUSSION

Characterization of Laboratory-Prepared Samples

Effect of Elapsed Time on Initial Peel Strength—In the laboratory, the strength of liquid-adhesive seams increases over the first week or two after fabrication.[7] In the present study, the creep tests are to be performed on seam specimens that have reached constant strength. Thus, an experiment was conducted using Tape System 1 and Tape System 2 applied to cleaned, primed EPDM wherein peel strength was determined over a period ranging from 0.25 to 56 days. The specimens were prepared, held and tested at ambient laboratory conditions. Four specimens of each tape system were tested at each measurement point. The results are presented in Table 1 and plotted in Figure 1. The data points in the figure represent the averages of the four measurements and the error bars represent plus and minus one standard deviation from the average.

As is evident in Figure 1, the strengths of the specimens

Tape System	Time days	Strength, kN/m				Strength, lbf/in.				CoV[c]
		min	max	ave[a]	sd[b]	min	max	ave[a]	sd[b]	%
1	¼	0.68	0.80	0.72	0.06	3.9	4.6	4.1	0.34	8.3
	1	0.87	1.06	0.95	0.08	5.0	6.1	5.4	0.46	8.4
	3	1.32	1.53	1.46	0.09	7.5	8.7	8.3	0.51	6.2
	7	1.60	1.74	1.67	0.07	9.1	9.9	9.5	0.40	4.2
	14	1.70	1.79	1.75	0.04	9.7	10.2	10.0	0.23	2.3
	21	1.79	1.89	1.84	0.05	10.2	10.8	10.5	0.29	2.7
	28	1.74	1.86	1.81	0.05	9.9	10.6	10.3	0.29	2.8
	35	1.76	1.80	1.78	0.02	10.1	10.3	10.2	0.11	1.1
	42	1.86	1.92	1.90	0.03	10.6	11.0	10.8	0.17	1.6
	56	1.71	1.87	1.78	0.07	9.8	10.7	10.2	0.40	3.9
2	¼	1.18	1.34	1.25	0.07	6.7	7.7	7.1	0.40	5.6
	1	1.52	1.69	1.62	0.07	8.7	9.7	9.3	0.40	4.3
	3	1.84	2.08	1.96	0.10	10.5	11.9	11.2	0.57	5.1
	7	1.84	2.23	2.05	0.19	10.5	12.7	11.7	1.08	9.3
	14	2.02	2.31	2.19	0.14	11.5	13.2	12.5	0.80	6.4
	21	2.11	2.29	2.20	0.09	12.0	13.1	12.6	0.51	4.1
	28	2.22	2.41	2.30	0.09	12.7	13.8	13.1	0.51	3.9
	35	2.03	2.31	2.17	0.13	11.6	13.2	12.4	0.74	6.0
	42	2.11	2.42	2.31	0.14	12.0	13.8	13.2	0.80	6.1
	56	1.88	2.34	2.10	0.19	10.7	13.4	12.0	1.08	9.0

[a] Average of four measurements.
[b] sd indicates standard deviation. (It is calculated as $[\Sigma(x_i - x_{av})^2/(n-1)]^{1/2}$.)
[c] CoV indicates coefficient of variation. (It is calculated as the ratio of the standard deviation to the mean times 100.)

***Table 1.** Peel strength versus elapsed time after fabrication.*

increased rapidly at first, but the rate of increase fell substantially after three days. Stabilization appeared to have been achieved by about 14 days. At this time, Tape System 1 had a strength of 1.75 kN/m (10.0 lbf/in.) and Tape System 2 had a strength of 2.19 kN/m (12.5 lbf/in.) (Table 1). Figure 1 also includes strength-time data from Martin et al.[7] for a butyl-based liquid adhesive applied to cleaned EPDM. The two tape systems had seam strengths greater than that of the liquid adhesive when the strengths reached constant values.

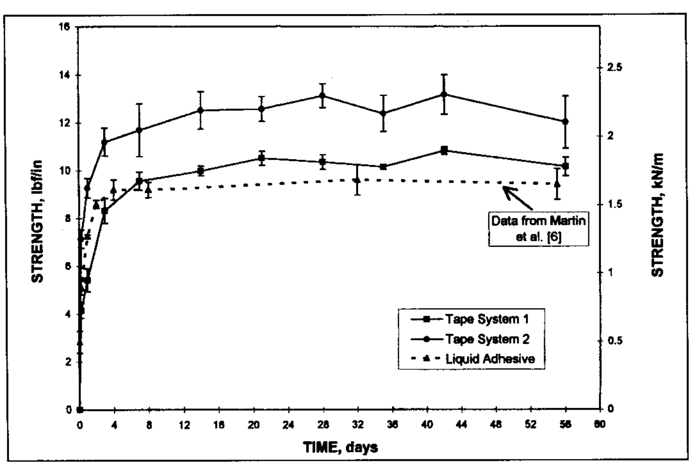

***Figure 1.** Initial peel strength versus elapsed time at ambient laboratory conditions (about 23°C or 73°F and 40-50 percent RH). The data for the tape-bonded specimens are compared to those for butyl-based liquid-applied adhesive specimens taken from Martin et al.[7]*

The failure modes of both tape systems were comparable during the peel tests. At one-quarter day and at one day, the specimens failed adhesively. At three days, the mode was mixed with some areas failing cohesively and others adhesively. When strength stabilization occurred, in the case of Tape System 1, the failure mode was essentially cohesive over the entire bond area. In the case of Tape System 2, it was generally about 80 to 85 percent cohesive.

Typical failure modes for the two tape systems after strength stabilization are shown in Figure 2. Tape System 1, whose failure mode is essentially all cohesive, is shown at the top. Tape System 2, which exhibited some adhesive failure, is given at the bottom of the photo. In the case of Tape System 2, no pattern was observed as to the areas of the various specimens over which adhesive failure occurred. However, the adhesive failure of some bond areas contributed to the wider scatter in the strength data for Tape System 2 vis-a-vis Tape System 1. Note in Table 1 that, for times of seven days or more, the coefficients of variation (CoV) are greater for Tape System 2 than for Tape System 1. It was observed during peel testing that the bond areas of the Tape System 2 specimens experiencing adhesive failure had lower strengths than the areas of cohesive failure. Thus, assuming other factors (e.g., surface cleanness) to be equal, specimens with greater areas of adhesive failure would have lower average peel strengths than those of specimens having less adhesive failure. The extent of the bond areas having adhesive failure varied somewhat among the four specimens in a Tape System 2 set which, in turn, increased the scatter in the peel strength data for the set.

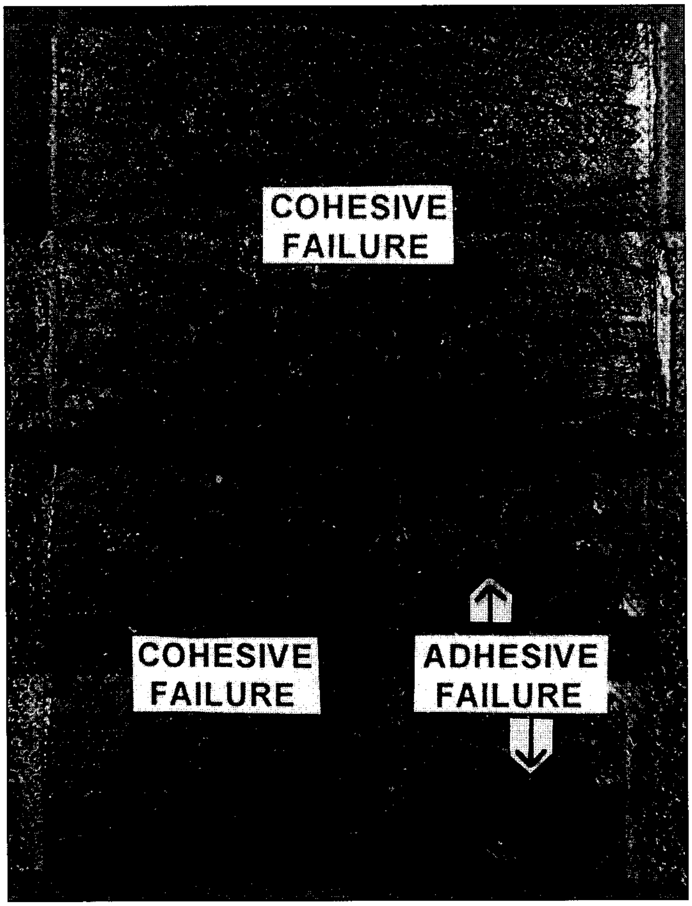

Figure 2. Photograph of the typical failure modes for both tape systems after strength stabilization. The failure of Tape System 1 was essentially all cohesive (upper specimen); whereas the failure of Tape System 2 generally had some areas of adhesive failure (lower specimen).

Statistical analysis of the data in Table 1 was performed and the strength was found to follow very closely the model,

$$\text{Strength} = S_{\text{ultimate}} \bullet (1\text{-exp}(-b \bullet \text{time}))^{c},$$

where S_{ultimate} (i.e., ultimate strength), b, and c are empirical constants. Table 2 provides values of the constants along with the residual standard deviations for the fitted models. Figure 3 shows the curves fitted to the average data points. Note that the data points for both tape systems fall on or close to the fitted curves.

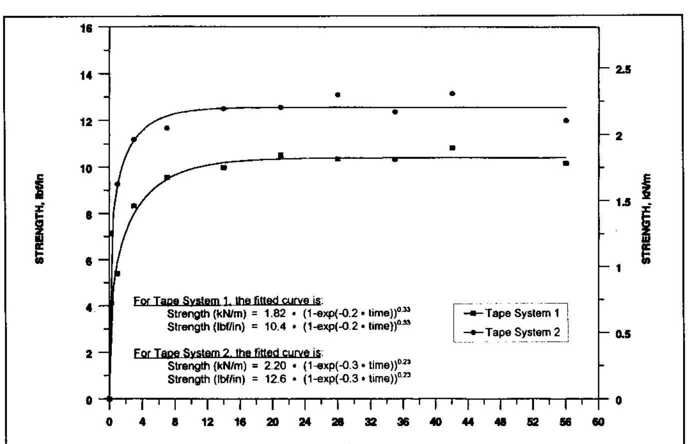

Figure 3. Fit of the elapsed-time data to the analytical model.

Parameter	Parameter Estimates[a] Tape System 1	Tape System 2
S_{ultimate} (kN/m)	1.82 (0.016)	2.20 (0.026)
S_{ultimate} (lbf/in.)	10.4 (0.09)	12.6 (0.15)
b (days^{-1})	0.20 (0.03)	0.30 (0.08)
c	0.33 (0.026)	0.23 (0.03)
rsd[b]	0.41	0.74

[a] Values in parentheses are standard deviations.
[b]rsd = residual standard deviation (It is a measure of the closeness of the points to the fitted model. It is calculated by summing the squared difference between each data point and the corresponding value of the fitted curve, dividing by (n-k) where n is the number of data points and k is the number of fitted parameters (e.g., two for a straight-line fit and three for a quadratic fit), and then taking the square root.)

***Table 2.** Results of the analysis of the peel strength versus elapsed-time data.*

The model provides an estimate of the ultimate strength of an "average" specimen. For Tape System 1 and Tape System 2, the ultimate strengths are estimated to be 1.82 kN/m (10.4 lbf/in.) and 2.20 kN/m (12.6 lbf/in.), respectively, with standard deviations of 0.016 kN/m (0.09 lbf/in.) and 0.026 kN/m (0.15 lbf/in.).

Tape System 1 reached 99 percent of its estimated ultimate value in 17.6 days (and 98 percent at 14.2 days). Tape System 2 reached ultimate strength more rapidly; it reached 99 percent in 10.5 days. Thus, these data indicate that, before conducting creep-rupture experiments using these tapes, a conservative waiting period of three weeks would be adequate to assure that strength has stabilized.

Effect of Applied Pressure on Peel Strength—An experiment was conducted to measure the peel strengths of specimens that were pressed together for 10 s under a range of pressures varying from 0.005 to 2.1 MPa (0.73 to 300 lbf/in.^{2}). For this short-term experiment, the elapsed time before testing was 14 days which was selected on the basis of the previously described results of the effect of elapsed time on strength. With the exception of the lowest value, pressure was applied to the specimens using the press described in the Appendix. The lowest pressure was applied by placing a piece of sheet metal of appropriate size and mass on the bond area of the specimens. For purposes of comparison, a set of specimens was also pressed together with a roller used in the field by roofing mechanics during seam fabrication. In the present study, the maximum pressure was three times greater than the control; whereas the minimum value was only slightly greater than zero and represented a pressure that might be exerted on a horizontal surface with a slight swipe of the palm of the hand.[15]

The results of the pressure tests are given in Table 3 and shown in Figure 4. They indicate that, over the range selected, varying pressure had no practical effect on the peel strength of the seam specimens. This finding contrasted with the results of a previous NIST experiment using a butyl-based liquid adhesive wherein specimens pressed at a relatively low pressure of 1.7 kPa (0.25 lbf/in.^{2}) were stronger than those fabricated at a pressure of 0.69 MPa (100 lbf/in.^{2}).[15] Reasons for this observation in the previous NIST study were not explored. Based on the present results, incorporation of residual stress in tape system specimens

Tape System	Press. MPa (psi)	Strength, kN/m min	max	ave[a]	sd[b]	Strength, lbf/in. min	max	ave[a]	sd[b]	CoV[c] %
1	0.005 (0.73)	1.73	1.95	1.83	0.10	9.9	11.1	10.4	0.57	5.5
	0.26 (37.5)	1.72	1.85	1.77	0.06	9.8	10.6	10.1	0.34	3.4
	0.52 (75)	1.67	1.79	1.73	0.05	9.5	10.2	9.9	0.29	2.9
	0.69 (100)	1.70	1.79	1.75	0.04	9.7	10.2	10.0	0.23	2.3
	1.0 (150)	1.66	1.77	1.72	0.05	9.5	10.1	9.8	0.29	2.9
	2.1 (300)	1.62	1.80	1.71	0.08	9.3	10.3	9.8	0.46	4.7
	roller	1.73	1.82	1.79	0.04	9.9	10.4	10.2	0.23	2.2
2	0.005 (0.73)	2.02	2.22	2.10	0.08	11.5	12.7	12.0	0.46	3.8
	0.26 (37.5)	2.07	2.42	2.25	0.18	11.8	13.8	12.8	1.03	8.0
	0.52 (75)	2.09	2.31	2.20	0.09	11.9	13.2	12.6	0.51	4.1
	0.69 (100)	2.02	2.31	2.19	0.14	11.5	13.2	12.5	0.80	6.4
	1.0 (150)	1.89	2.25	2.10	0.15	10.8	12.8	12.0	0.86	7.1
	2.1 (300)	2.16	2.30	2.22	0.06	12.3	13.1	12.7	0.34	2.7
	roller	1.95	2.40	2.23	0.20	11.1	13.7	12.7	1.14	9.0

[a] Average of four measurements.
[b] sd indicates standard deviation.
[c] CoV indicates coefficient of variation.

Table 3. *Peel strength versus pressure applied during fabrication.*

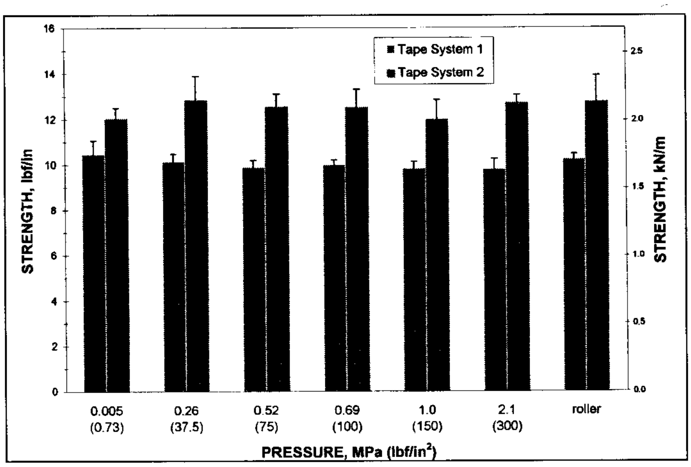

Figure 4. *Peel strength versus applied pressure. The roller pressure is about 0.69 MPa (100 lbf/in.²).*

fabricated at higher pressures does not appear to be a problem.

From a practical viewpoint, the implications of the lack of a pressure effect on short-term peel strength are positive. The human element associated with applying seams in the field under a variety of environmental conditions could lead to considerable variation in the pressures applied by roofing mechanics over the course of a work day or from day to day. The results here imply that adequate strengths of tape-bonded seams should be achievable over a rather broad range of pressures that roofing mechanics might apply during seam operations. The effect of pressure on creep-rupture response will be investigated in Phase II of the joint research study.

Effect of Duration of Applied Pressure on Peel Strength—The duration of pressure application during seam fabrication has generally been 10 s in NIST laboratory experiments. Consistent with this past experience, 10 s was selected as the control duration in this study. One experiment was conducted in which the pressure was constant at 0.69 MPa (100 lbf/in.²) and the duration of applied pressure was varied from 2.5 to 20 s. The elapsed time before testing was 14 days. The duration of 2.5 s may be on the high end of that applied in the field.

The results are given in Table 4 and plotted in Figure 5. As can be seen, the duration of applied pressure had no practical effect on the strengths of specimens prepared with either tape system. Again, from a practical viewpoint, this lack of effect is positive, as roofing mechanics may not exert strict control over this factor in the field.

Effect of EPDM Surface Condition on Peel Strength—Manufacturer's recommendations for the proper application of tape systems require that the EPDM rubber be well cleaned and then primed before application of the tape. In practice, these recommendations may not be adequately

Tape System	Time	Strength, kN/m				Strength, lbf/in.				CoV[c]
	s	min	max	ave[a]	sd[b]	min	max	ave[a]	sd[b]	%
1	2.5	1.60	1.76	1.69	0.07	9.1	10.1	9.7	0.40	4.1
	5	1.66	1.75	1.69	0.04	9.5	10.0	9.7	0.23	2.4
	10	1.68	1.77	1.73	0.05	9.6	10.1	9.9	0.29	2.9
	20	1.74	1.84	1.77	0.05	9.9	10.5	10.1	0.29	2.8
2	2.5	2.04	2.38	2.26	0.15	11.6	13.6	12.9	0.86	6.6
	5	2.15	2.34	2.22	0.08	12.3	13.4	12.7	0.46	3.6
	10	2.06	2.19	2.13	0.07	11.8	12.5	12.2	0.40	3.3
	20	2.10	2.23	2.23	0.11	12.0	13.3	12.7	0.63	4.9

[a] Average of four measurements.
[b] sd indicates standard deviation.
[c] CoV indicates coefficient of variation.

Table 4. Peel strength versus duration of applied pressure.

followed. An experiment was performed to investigate the effect of inadequate surface preparation on the peel strengths of the specimens. Six surface conditions were included in the experiment as given in Table 5. The combinations of surface preparation variables ranged from well cleaned and primed to partially contaminated and not primed. All peel tests were conducted when the specimens were 14 days old.

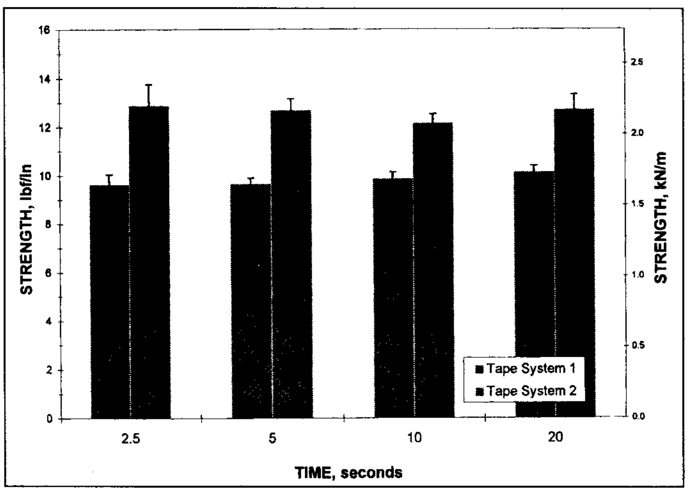

Figure 5. Peel strength versus the duration of applied pressure.

On the job, current practices for the application of tape systems employ one of two EPDM surface preparation techniques.[4,16] The first, a two step process, involves cleaning the rubber with a solvent and subsequently applying the primer with a brush, cloth, or synthetic scrubbing pad. The second technique has only a single step in which the EPDM is cleaned and primed by scrubbing it with the synthetic scrub pad saturated with primer. Experience has shown that, in either the single- or two-step process, roof mechanics may apply the primer more than once using the scrub pad. Note in Table 5 that surface preparation condition Nos. 2 and 5 incorporated scrubbing with a pad.

Condition No.	Condition Description
1	EPDM was well cleaned and primed using a drawdown technique. This condition was considered to be the control.
2	EPDM was well cleaned, scrubbed with a scrub pad soaked in primer, and additionally primed using a drawdown technique.
3	EPDM was well cleaned and not primed.
4	EPDM was uncleaned and primed using a drawdown technique.
5	EPDM was uncleaned, well scrubbed with a scrub pad soaked in primer, and additionally primed using a drawdown technique.
6	EPDM was partially cleaned and unprimed. Partially cleaning was used in lieu of not cleaning as test specimens could not be prepared with the uncleaned rubber. Partial cleaning was achieved by pressing seam tape to the as-received EPDM surface. Loose release agent on the EPDM adhered to the removed tape. New tape was used to form a specimen.

Table 5. Surface conditions of tape-system samples.

The results of the surface condition experiment are given in Table 6 and plotted in Figure 6. Surface preparation condition No. 1 was taken as the control. The average peel strengths of the Tape System 1 and Tape System 2 controls were 1.83 and 2.23 kN/m (10.4 and 12.7 lbf/in.). These values were essentially identical to the strengths of an "average" specimen calculated using the models presented earlier. The results of the surface condition experiment were analyzed by comparing the average peel strength of the controls with the average strengths found for each of the other surface preparation conditions (for each tape system). The significance of the differences* was evaluated using the Student's t-test.[17]

Surface preparation condition Nos. 1 and 2 differed only in that condition No. 2 incorporated an intermediate step

**If two quantities are said to be "significantly different at the p level," it means that, if the true values of the quantities are indeed identical, then there is only a 100p percent chance of obtaining values for the two quantities as different as the observed values. Thus, if the chosen value of p is small (say 0.05) and the analysis indicates a significant differemce, one would feel reasonably safe in assuming that the true values for this experiment are indeed different.*

Tape System	Cond. no.	Strength, kN/m				Strength, lbf/in.				CoV[c]
		min	max	ave[a]	sd[b]	min	max	ave[a]	sd[b]	%
1	1	1.76	1.87	1.83	0.05	10.1	10.7	10.4	0.29	2.7
	2	1.72	1.87	1.81	0.07	9.8	10.7	10.3	0.40	3.9
	3	0.92	1.42	1.18	0.23	5.3	8.1	6.7	1.31	19.5
	4	1.40	1.78	1.57	0.16	8.0	10.2	9.0	0.91	10.2
	5	1.54	1.83	1.68	0.12	8.8	10.4	9.6	0.69	7.1
	6	1.06	1.29	1.17	0.11	6.1	7.4	6.7	0.63	9.4
2	1	2.13	2.29	2.23	0.07	12.2	13.1	12.7	0.40	3.1
	2	2.13	2.59	2.32	0.22	12.2	14.8	13.2	1.26	9.5
	3	1.07	1.23	1.17	0.08	6.1	7.0	6.7	0.46	6.8
	4	0.49	1.17	0.81	0.35	2.8	6.7	4.6	2.00	43.2
	5	2.11	2.41	2.28	0.13	12.0	13.8	13.0	0.74	5.7
	6	0.61	0.68	0.64	0.03	3.5	3.9	3.7	0.17	4.7

[a] Average of four measurements.
[b] sd indicates standard deviation.
[c] CoV indicates coefficient of variation.

Table 6. *Peel strength versus rubber surface condition.*

of applying primer to the cleaned EPDM surface using a scrub pad. This comparison was performed to investigate whether strength and failure mode were affected by the two different methods of applying the primer to the EPDM surface. The step of adding additional primer using the drawdown technique was incorporated to assure that the amounts of primer applied under the two conditions were comparable. For both tape systems, the results showed no statistically significant differences (at the 0.6 and 0.4 levels for Tape System 1 and Tape System 2, respectively) between the average strengths of the two sets of specimens. For both tape systems, the mode of failure was cohesive. These results indicate that the strength of the specimens and locus of failure were not affected by applying the primer to the cleaned EPDM surface with either a drawdown blade or scrub pad.

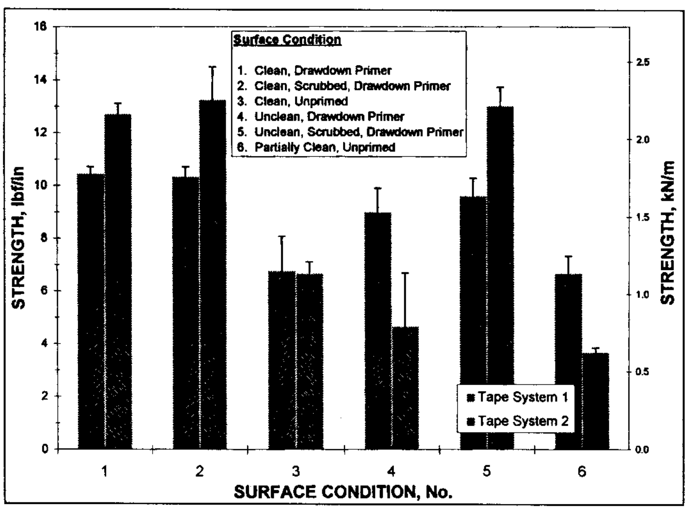

Figure 6. *Peel strength versus surface condition.*

Surface preparation condition No. 3 had cleaned rubber, but no primer. It is evident in Figure 6 that the omission of primer had an adverse effect on peel strength: the strength of Tape System 1 decreased by 35 percent and that of Tape System 2 dropped by 48 percent. The differences were statistically significant at the 0.01 confidence level. Without primers, the mode of failure was adhesive. These results illustrate the importance of using primers when forming seams with these two tape systems.

The EPDM surfaces prepared using condition No. 4 were not cleaned but were primed. Here there was an adverse effect on peel strength, particularly in the case of Tape System 2. Decreases of 13 percent and 64 percent (statistically significant at the 0.05 and 0.01 levels) were observed for Tape System 1 and Tape System 2, respectively. All specimens failed adhesively. In the case of Tape System 1, at least in this instance, the application of the primer using the drawdown technique apparently caused sufficient displacement of release agent from the EPDM surface that considerable bond strength was achieved, although it was statistically lower than the control. This was not the case with Tape System 2 where the peel strength was only about a third of that of the control. In fact, the percent decrease in strength due to the uncleaned surface was greater than that experienced by seams prepared using butyl-based liquid adhesives on uncleaned rubber. In the case of the liquid adhesive, peel strengths of surface-contaminated EPDM have been measured to be about one-half to three-quarters of that of well cleaned EPDM.[7,13] The results for the tape systems again illustrate the importance of cleaning the EPDM. If not properly cleaned, the peel strength is significantly reduced, and the failure is adhesive.

Surface preparation condition No. 5 was similar to a field practice wherein the roofing mechanic uses a synthetic scrub pad, in a single-step process, to apply the primer to the uncleaned EPDM surface to clean and prime it. It was of interest to determine whether applying the primer to the uncleaned surface with a scrub pad, followed by application of additional primer, resulted in strengths and failure modes comparable to those whereby the EPDM was first cleaned and then primed in a two- step process (condition Nos. 1 and 2). In comparison to the controls (condition No. 1), Tape System 1 showed a slight decrease in strength (8 percent), which was not statistically significant at the 0.05 level, but was statistically significant at the 0.1 level. Tape System 2 had a slight increase (2 percent) in

Sample No.	Age years	Location	Membrane Supplier	Type of Membrane Securement
F1	6.5	Wichita	1	Adhered
F2	1	Manchester	1	Mechanically fastened
F3	0.5	Manchester	1	Mechanically fastened
F4	1.5	Manchester	1	Mechanically fastened
F5	4.5	Milwaukee	2	Adhered
F6	6	Milwaukee	2	Adhered
F7	5	Milwaukee	2	Loose-laid
F8	1	Chicago	3	Loose-laid
F9	6	Phoenix	4	Loose-laid

Table 7. *Description of the EPDM roofs from which tape-seam samples were removed.*

strength, which was also not statistically significant (0.4 level). Similarly, in comparison to condition No. 2, both tape systems showed slight decreases in strength (7 and 2 percent, respectively), which were not statistically significant (0.1 and 0.6 levels, respectively). All specimens cleaned and primed in the single-step process failed cohesively. These results indicated that scrubbing the uncleaned EPDM with the primer-saturated pad followed by the drawdown technique prepared the surface such that the peel strength and locus of failure were comparable to that of specimens cleaned in one step and primed in another (condition Nos. 1 and 2).

Finally, surface preparation condition No. 6 incorporated partially cleaned and unprimed EPDM. This condition was included in the experiment because a measurable bond could not be formed when the EPDM was uncleaned and unprimed. Partial cleaning of the EPDM took advantage of this finding, and was carried out by placing tape on the uncleaned surface and applying pressure. When the unbonded tape was removed from the EPDM, some of the release agent was stuck to the tape surface. Application of a fresh piece of tape to the resultant EPDM allowed for bonding to the contaminated rubber surface.

As is evident in Figure 6, the strengths of the partially cleaned, unprimed specimens were, not unexpectedly, less than those of the controls. The strength of Tape System 1 decreased by 35 percent and that of Tape System 2 decreased by 71 percent. The differences were statistically significant at the 0.01 level, and the failure mode was adhesive. The results again illustrate the importance of properly cleaning and priming the EPDM. If cleaning and priming are improperly performed, strength will be significantly decreased. The effect of both surface cleaning and priming on creep-rupture performance will be investigated in the next phase of the study.

Characterization of Samples Removed from Roofs in Service

Concurrent with the investigations of peel strength of laboratory-prepared samples, inspections of 14 EPDM roofs having tape-bonded seams were made. The inspections were arranged and accompanied by roofing contractors who installed the membranes. The roofs were located in Boston, Mass., Chicago, Ill., Manchester, N.H., Milwaukee, Wis., Phoenix, Ariz., and Wichita, Kan. Thirteen of the 14 roofs had seams that were comparable to the tape systems used today, and ranged in age from about 0.5 to 8 years. The other roof was 16 years old. This tape system was a butyl gum rubber which is no longer commercially available.[4]

In all cases, the roofing contractors spoke positively about the roofs' performance for the relatively short periods of time that the tapes have been in place. Specifically, no leaks through the seams were reported for any of the roofs. Nevertheless, some contractors were cautious in remarking that the tapes had not been in place long in comparison to the expected service of the roofs.

The observations from the roof inspections were consistent with the contractors' comments. The seams were seen to be in acceptable condition. All appeared to be tight with no evidence of disbonding and, with minor exception, patches on the seams were not observed. In one case, there was some patching, but it may have been due to sampling of the seams after fabrication. Little evidence of rippling, a source of peel stress,[7] was observed. Where it was noticed, the ripples were not large in size and the seam areas having the ripples were bonded. Additionally, "t-joints" where seams overlap were found to be bonded.

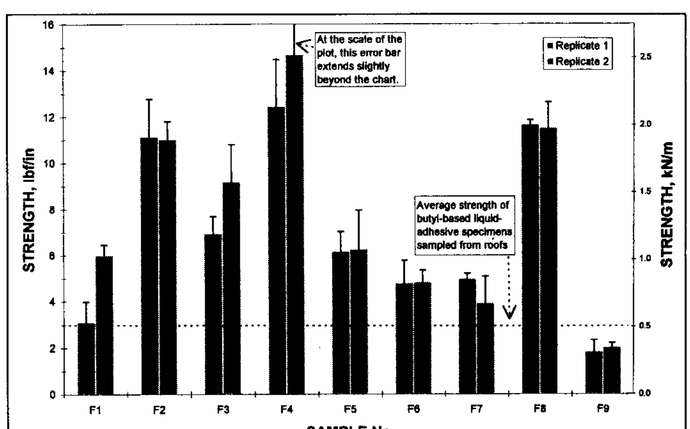

Figure 7. *Peel strength of samples removed from roofs in service. The data are compared to the average peel strength of butyl-based liquid-adhesive specimens sampled from roofs in other studies.*[18-20]

A pair of samples from two different seams were removed from 10 of the 14 roofs** and their peel strengths were measured in the laboratory. For each roof, the pair of samples was considered to have experienced the similar exposure. Table 7 lists characteristics of the sampled roofs such as age and location. Table 8 summarizes the results of the measurements, and Figure 7 plots average strength. The average strengths of the samples ranged from about 0.32 to

***Difficulties in preparation of peel specimens precluded conducting tests on samples removed from one roof. Tables 7 and 8 list only nine specimens.*

Sample No.	Replicate No.	Strength, kN/m				Strength, lbf/in.				CoV[c]
		min	max	ave[a]	sd[b]	min	max	ave[a]	sd[b]	%
F1	1	0.36	0.70	0.54	0.15	2.1	4.0	3.1	0.86	27.8
	2	0.94	1.11	1.05	0.08	5.4	6.3	6.0	0.46	7.6
F2	1	1.71	2.35	1.95	0.29	9.8	13.4	11.1	1.66	14.9
	2	1.76	2.08	1.93	0.14	10.1	11.9	11.0	0.80	7.3
F3	1	1.13	1.41	1.21	0.13	6.5	8.1	6.9	0.74	10.7
	2	1.20	1.85	1.61	0.28	6.9	10.6	9.2	1.60	17.4
F4	1	1.88	2.53	2.18	0.35	10.7	14.4	12.4	2.00	16.1
	2	2.03	2.87	2.57	0.39	11.6	16.4	14.7	2.23	15.2
F5	1	0.93	1.24	1.08	0.15	5.3	7 1	6.2	0.86	13.9
	2	0.83	1.36	1.10	0.30	4.7	7.8	6.3	1.71	27.3
F6	1	0.63	1.05	0.84	0.17	3.6	6.0	4.8	0.97	20.2
	2	0.75	0.96	0.85	0.09	4.3	5.5	4.9	0.51	10.6
F7	1	0.85	0.93	0.87	0.04	4.9	5.3	5.0	0.23	4.6
	2	0.42	0.87	0.69	0.20	2.4	5.0	3.9	1.2	29.7
F8	1	2.01	2.08	2.04	0.03	11.5	11.9	11.6	0.17	1.5
	2	1.75	2.23	2.01	0.20	10.0	12.7	11.5	1.14	10.0
F9	1	0.25	0.45	0.32	0.09	1.4	2.6	1.8	0.51	28.1
	2	0.33	0.40	0.35	0.03	1.9	2.3	2.0	0.17	8.6

[a] Average of four measurements.
[b] sd indicates standard deviation.
[c] CoV indicates coefficient of variation.

Table 8. *Peel strength of field samples.*

2.57 kN/m (1.8 to 14.7 lbf/in.). That is, these field specimens had strengths that were both higher and lower than the strengths measured for laboratory specimens prepared with cleaned, primed EPDM (see, for example, Tables 1 and 6). Variation in the strength of samples removed from roofs is not unexpected. Similar results have been found for butyl-based liquid-adhesive seams taken from roofs, and have been attributed to the variability of the manual labor and environmental conditions during seam fabrication.[18] Note in Table 8 that, for many of the specimen sets, the coefficients of variation ranged from about 15 to 30 percent. This was much higher than the coefficients of variation determined for sets of laboratory-prepared samples (e.g., Table 1). On the other hand, in spite of this relatively large variation in the data for the specimens in many of the individual sample sets, six of the nine pairs of samples had comparable average strengths.

The strength values for the field tape-bonded samples may be compared with those measured for butyl-based liquid-applied adhesive samples taken from roofs. The comparison is considered preliminary as the number of roofs having tape-bonded seams are limited. Note in Figure 7 the horizontal dashed line plotted at about 0.5 kN/m (3 lbf/in.). This value is the approximate average peel strength previously reported for field samples of butyl-based liquid-applied adhesive seams.[18-20] The range of values for these measurements was from 0.23 to 1.2 kN/m (1.3 to 6.9 lbf/in.). With the exception of one sample (F9) in the present study, the tape-bonded seam samples had strengths above the average of the liquid-adhesive seams. Samples F2, F3 (Replicate 2), F4 and F8 had strengths about 3 to 4 times higher. Samples F1 (Replicate 1), F5, F6 and F8 were about 1.5 to 2 times stronger than the average strengths of the liquid-adhesive samples. In this latter case, the strengths of the tape-bonded samples were comparable to those in the upper end of the range of strengths for the liquid-adhesive samples in the cited studies.[18-20]

The predominant mode of failure of the tape-bonded field samples during peeling was adhesive indicating that surface effects played a major role in the specimen delamination. Only samples F1 (Replicate 1), F2 and F8 failed cohesively. The finding that adhesive failure predominated was in contrast to the findings for the laboratory-prepared cleaned and primed samples wherein cohesive failure was observed. But the finding for the tape-bonded field samples was consistent with past experience with butyl-based liquid-applied adhesives[18,19] in that field seams have often shown adhesive failure in peel tests. In the case of the current tape samples from the field, the EPDM surfaces may have been less adequately prepared than those readied in the laboratory. However, it cannot be ruled out that the cohesive strength of the tapes increased due to aging. Given that the fabrication of field seams is quite dependent on workmanship, it may be reasonable to assume that at least some of the field tape specimens failed adhesively due to inadequate surface preparation. The need for roof mechanics to follow instructions for proper surface preparation cannot be overemphasized.

SUMMARY AND CONCLUSIONS

The use of preformed, 100 percent-solids tapes for fabricating seams of EPDM membranes has increased in recent years. A joint industry-government research study has been initiated to compare the performance of tape-bonded and liquid-adhesive-bonded seams in EPDM roofing membranes, and to develop a test protocol and criteria for evaluating the performance of such tape-bonded seams. The joint study will focus on the determination of the creep-response of specimens subjected to varying peel loads and prepared under a variety of conditions. Before conducting creep experiments, it was necessary to assure that the strength of the specimens had stabilized. This paper presents the results of initial laboratory tests to characterize peel strength.

The laboratory experimentation was performed using two commercial tape systems (i.e., tape and primer combinations) that are available for EPDM roofing today. The initial peel strength of tape-bonded specimens was determined as a function of elapsed time, applied pressure, duration of applied pressure, and surface condition of the EPDM rubber. The following conclusions were drawn from the results of the investigations:

- Peel strength increased for a relatively short time after sample preparation. Before conducting creep experiments, a conservative waiting period of three weeks at ambient laboratory conditions is adequate to assure that strength has stabilized.
- Peel strength was unaffected by either the amount of pressure applied or the duration of applied pressure. These results implied that acceptable strengths of tape-bonded seams should be achievable over the range of pressures that mechanics might exert during seam fabrication.
- Peel strength was adversely affected (i.e., it was lower) when the EPDM surface was not adequately cleaned and/or primed. The results illustrated the importance of proper EPDM surface preparation (i.e., cleaning and priming) during seam installation.

In addition to the measurements of laboratory-prepared samples, peel strengths were determined for nine tape-bonded seam samples removed from roofs having ages of 0.5 to 6.5 years. All roofs were performing satisfactorily. Some of the seam strengths were higher and some were lower than the strengths measured for laboratory specimens prepared with cleaned, primed EPDM. For the limited number of tape-bonded seams examined, with one exception, the samples had strengths above the average of butyl-based liquid-adhesive seams removed from roofs in previous studies. The majority of the tape-bonded specimens in the present study failed adhesively, indicating that the EPDM surfaces to be bonded may have been less-than-adequately prepared, or that aging of the tape results in increased cohesive strength. Where the former reasoning is true, the finding emphasizes the need for roofing mechanics to follow instructions for proper surface preparation during tape-bonded seam fabrication.

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APPENDIX—EXPERIMENTAL DETAILS

This Appendix describes the procedures used to prepare tape-bonded seam specimens using well-cleaned rubber. During the experimentation, some of the specific steps were altered to determine whether there was an effect on peel strength. For example, in one experiment, specimens were prepared with surface-contaminated rubber instead of well-cleaned rubber. Such changes to the application procedures are described in the main text of the paper along with the data presentation and discussions.

Laboratory Seam Specimen Preparation

Cleaning of the EPDM Rubber Surface—The EPDM rubber roofing material was a commercial rubber sheet having a nominal thickness of 1.5 mm (0.060 in.). The sheet was non-reinforced and had a talc-like release agent on its surfaces. The EPDM was cleaned using a residential-style clothes washing machine followed by wiping with a cloth soaked in heptane. Previous studies[7,21,22] in our laboratories have shown that scrubbing with a detergent and water is an effective first step in removing the release agent from EPDM surfaces. The use of a washing machine was incorporated in the cleaning procedure as a labor-saving step. In using the washing machine, 10 pieces of EPDM having dimensions of 150 x 200 mm (6 x 8 in.) were placed in the machine tub along with detergent and 10 to 12 household cotton towels, 375 x 750 mm (15 x 30 in.) in size. The towels were intended to provide an abrasion action on the EPDM. The machine cycle was 30 minutes long and was divided almost equally into wash and rinse subcycles. A hot-cold water mix was used which provided a water temperature of about 50°C (122°F). After removal from the washing machine, the EPDM sections were placed on a laboratory bench overnight (or longer) to dry. Just before fabrication of the seam specimens, the EPDM surface was further cleaned by rubbing with a cloth soaked with reagent grade heptane.

Measurement of Surface Cleanness—The technique described by Martin et al.[7,8] was used to quantify the cleanness of the rubber surface with regard to removal of release-agent particles. The technique uses computer-image processing to measure the reflectance of tungsten light from the surfaces of the EPDM rubber strips. Light reflection from the black EPDM surface increases with increasing contamination by the white release-agent particles. Reflectance is quantified according to a grayscale output from the image processor. The grayscale value is zero for black and 255 for a white surface. In the current study, the grayscale level for the cleaned EPDM was 38, which compared well to values (30-33) in previous NIST studies.[7,13] Subsequent scanning electron microscopy analysis of the surfaces of selected pieces indicated that they were essentially free of particulate contamination typical of release agent.

Tape System Application and Seam Fabrication—One of two commercially available tape systems (i.e., tape and primer combinations) was used to fabricate the seam specimens. The tapes, both with widths of 75 mm (3 in.), were set in place such that the direction of the rolls was perpendicular to the length of the resulting T-peel specimens. Using a drawdown blade technique with the EPDM held firmly on a vacuum table, the primer was applied to the bonding section of the EPDM rubber sheet (Figure A1). The thicknesses of applied primer were in accordance with each tape manufacturer's instructions: about 0.4 and 0.1 mm (0.016 and 0.004 in.) for Tape System 1 and Tape System 2, respectively.

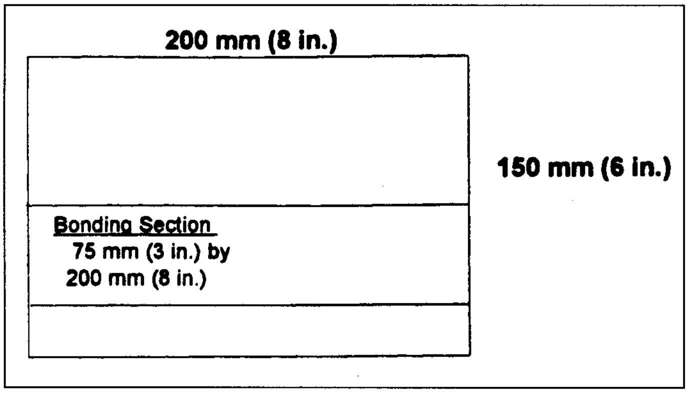

Figure A1. Plan-view of the bonding section of the EPDM sheet.

After the primer solvent evaporated (5-10 minutes), the tape was applied to the primed area of one of the two EPDM pieces used to fabricate the seam specimens. The two pieces were immediately mated together and pressed at 0.69 MPa (100 lbf/in.^{2}) for approximately 10 s. The press used in this study consisted of a pneumatic piston set in a testing machine which acted as a reaction frame. The top platen of the press was a plate mounted on the crosshead of the testing machine. The bottom platen of the press was a plate mounted on the piston. The piston was air-actuated using an electrically operated 4-way solenoid valve. This press was capable of applying pressures ranging from 0.21 to 2.1 MPa (30 to 300 lbf/in.^{2}). It was calibrated using a universal testing machine relating the air pressure applied in actuating the piston to the force exerted.

After the bonded section was removed from the press, it was cut into seven strips (i.e., test specimens) having widths of 25 mm (1 in.). Each specimen was maintained at ambient laboratory conditions, about 23°C (73°F) and 40-50 percent RH, until the peel strength was determined.

Field Seam Specimen Preparation
These test specimens were prepared by cutting adjacent strips 25 x 150 mm (1 x 6 in.) from the seam sections received from the field. The long dimension of the specimens was parallel to the direction of the field seam. This was necessary as most of the field seams were 75 mm (3 in.) in width or less. Twenty-five (25) mm (1 in.) of the cut seam was manually disbonded to provide "tabs" for holding the specimen in the grips of the testing machine.

Peel Strength
For a given seam sample, the peel tests were conducted on quadruplicate specimens at room temperature (about 23°C or 73°F) at a rate of 50 mm/min. (2 in./min.). The universal testing machine was equipped with hardware and software for recording and calculating strength data. Every day that tests were conducted, the calibration of the testing machine was verified using a 5-kgf (11-lbf) dead weight. After testing, each specimen was visually examined and the mode of failure, adhesive, cohesive, or a mixture of both, was noted.