THE EFFECT OF APPLICATION PARAMETERS ON ADHESIVE-BONDED SEAMS IN SINGLE-PLY MEMBRANES

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ABSTRACT

Adhesive-bonded seams in commercially-available EPDM and neoprene roofing membrane materials were prepared under a variety of application conditions to investigate the effects of the conditions on the resulting bond. Factors considered to have possible effects on the adhesive-bond, were lap length, surface contamination of the rubber, moisture, temperature, and voids in the seam. Lap shear specimens were tested in tension, because if was believed that such a test could provide comparisons between specimens fabricated under the various conditions. For each membrane material the load and ultimate elongation at specimen failure were compared in relation to the conditions under which the specimens were prepared or to the presence of voids in the seam.

The results indicated that, in most cases, application conditions had little effect on the measured load and ultimate elongation of the test specimens. In particular, specimens with voids had, in many cases, values of load and ultimate elongations comparable to those of the control specimens. Based on the results, the adequacy of the lap shear test to detect possible differences in bond strength due to differences in application conditions is questioned.

Over the last decade in the United States, the use of synthetic rubber sheets as the waterproofing component of low-sloped roofing systems has become common. Rubber membranes now account for 25 percent or more of the roofing membranes installed each year in the United States, with EPDM (ethylene propylene diene monomer) being the major generic rubber used.[1] In general, these membranes have performed satisfactorily for the limited period of time that they have been in service.[2] However, voluntary consensus standards, either prescriptive in nature or performance oriented, have yet to be developed in the United States. They are needed to assist in the design, selection, and evaluation of roofing systems incorporating rubber as well as other types of single-ply membranes.[2] In North America, industry requirements for rubber membrane materials have been prepared by the U.S. Rubber Manufacturers Association (RMA) and a standard specification has been developed by the Canadian General Standards Board (CGSB).

Rubber membranes may offer advantages for roofing such as increased extensibility, cold temperature flexibility, and light weight,[4] but they have some disadvantages. In particular, the waterproofing integrity of a single-ply membrane depends upon the seams remaining watertight over the intended service life.[4] A failure of one seam will result in a roof leak. One roof leak may result in wetting large areas of roof insulation and damage to other roof and building components or contents. The National Roofing Contractors Association (NRCA) has indicated that seam failure is the main problem which its membership reports regarding the performance of single-ply membranes.[1] Because of the importance of seams to the waterproofing integrity of single-ply rubber membranes, many authors have urged that test methods be developed to evaluate the long-term performance of seams in service.[5,6,7] Westley has indicated that the adhesion strengths of seams fabricated with contact cements for EPDM rubber are low and have little margin of safety.[6] However, he has not indicated the minimum strength requirements necessary for a seam to perform satisfactorily in service.

Nevertheless, to date, the development in the United States of consensus material specifications for rubber sheets used in low-sloped roofing has not considered requirements which pertain to the performance of seams made in the field.[3] A method for evaluating the service-life of seams is needed and should take into account the factors affecting their performance.

Senderling[8] has identified factors which affect the performance of seam to be:

- properties of the adhesive and membrane material;
- environmental conditions to which the seam is exposed in-service including stress, moisture, heat, low temperature, temperature cycling and chemical pollutants; and
- application parameters including workmanship and environmental conditions during seam fabrication and contamination of the rubber surface to which the adhesive is applied.

This paper presents the results of a laboratory study to investigate the effect of application parameters on the performance of the adhesive-bonded seam as measured in a laboratory test. A contact cement was used as it is, at present, the most common for vulcanized rubbers in the United States. The effect of primers was not included, since such a study has been reported.[9] Application parameters considered to affect seam performance include:

- Lap length, overlapping of adjacent sheets to form seams during construction may be less than adequate;
- Surface contamination, dirt, oils, grease, release agents and other surface contaminants may be present during adhesive application;
- Moisture, seams may be fabricated using sheets which are not adequately dry;
- Temperature, seams may be fabricated over a wide range of temperatures including those approaching freezing and

when the surface of a black membrane may be 158F (70C) or higher;

- Pressure, inadequate pressure may be applied to the seam during fabrication;
- Time, the time between application of the adhesive on the sheet and subsequent formation of the bond may vary and not be optimum;
- Adhesive thickness, excessively thick layers of adhesive may be applied during seam fabrication;
- Voids, skips in the adhesive layer result in unbonded areas in the seam;
- Fishmouths, improper alignment or placement of the sheets may result in incomplete contact between them.

A lap shear test of seams in tension was used. It has been reported that the ultimate strengths and elongations of lap shear specimens tested in tension may not be a reliable indicator of the performance of seams in service.[5,6,10] It was considered that, for this study, such a test could provide comparisons between specimens fabricated under the various conditions and a relative basis for investigating the effects of the various application parameters.

EXPERIMENTAL

The vulcanized rubber sheets are described in Table 1. Proprietary neoprene-based contact adhesives furnished for each rubber by the sheet manufacturer were used to form the seams in the test samples. Before applying the adhesive, the sheets were washed under water with a brush and allowed to dry overnight under ambient conditions. Except for sample No. 2, the sheets next were washed with hexane using a clean piece of cheesecloth. Sample No. 2 was washed using a solvent solution provided by the manufacturer. The adhesives were applied to the clean sheets as recommended by the manufactuerers. Once formed, the seam was immediately placed in a laboratory press for 4 to 5 seconds under 100 lbf/in² (0.7 mPa) pressure.

For most tests, the dimensions of the lap shear specimens were 6×1.5-inch (150×38mm) and the length of the bonded overlap was 2- inches (50mm). Other lap lengths were 4 and 8 inches (100 and 200mm). The specimens were tested in tension at room temperature using a universal testing machine at 0.2 inches per minute (0.5cm per minute). Seams were tested 7 days after fabrication. When the specimens were mounted, testing machine grips were set 1 inch (25mm) from the end of the seam lap. Thus, for the 6-inch (150mm) long specimens, the distance between grips was 4 inches (100mm). The recorded elongation was the distance between grips and not that occurring over the length of the seam.

The application parameters are given in Table 2. In general, four lap shear specimens were tested for each membrane material for each parameter.

RESULTS AND DISCUSSION

Figure 1 plots the load-elongation curves for specimens prepared as controls with the rubber cleaned and seams prepared as recommended. When the reinforced-EPDM sample No. 3 was elongated to less than 10 percent, the load increased to about 30 lbs per inch (5.2 N/mm), and then dropped abruptly when the reinforcement broke. The curves of load vs. elongation for seams prepared under other conditions or configurations *(Table 2)* were similar to those given in Figure 1. In some cases the load and ultimate elongation shifted at specimen failure when compared to that of the control. This shift was used to compare the behavior of the lap shear specimens in tension as related to the application parameter. Tables 3 to 6 present the values of load and ultimate elongation at specimen failure for samples No. 1 through 4, respectively, for the 12 application parameters. Included in these tables are the mean, range, standard deviation, and relative standard deviation as a percent of the mean for the load and ultimate elongation. Figures 2 through 5 present bar graphs of the average load and ultimate elongation at specimen failure for the four samples for each application parameter.

With one exception, the lap shear specimens tested in tension appeared to undergo adhesive failure, indicated by peeling of the adhesive from one of the rubber surfaces. Bond failure occurred through a progressive delamination starting at the ends of the lap and continuing towards the center along the axis of the specimen. This mode of failure has been previously described by Strong.[7] In one case, sample No. 3 with an 8-inch (200mm) lap, failure occurred in the rubber sheet outside the seam. Some seam delamination had occurred before the rubber sheet ultimately broke.

MEMBRANE MATERIAL SAMPLE NO. 1

The load-elongation data for the four specimens of sample No. 1 were acceptably reproducible for any application parameter. In general, the relative standard deviation for both the load and ultimate elongation at specimen failure were less than 15 percent and in most cases less than 10 percent *(Table 3)*.

As evident in Figure 2, the load at specimen failure either increased or decreased, when compared to the control, depending on the application parameter. The ultimate elongation decreased in all cases except that of the heated membrane material, parameter No. 10. The largest increase in load and ultimate elongation was found for the specimens heated before adhesive application. This may have been due to enhanced wetting, or interfacial contact, or the sheet at the higher temperature or because a temperature dependent chemical reaction occurred during adhesive application. Dirt, parameter No. 5, added to the surface before adhesive application produced the largest decrease in load and ultimate elongation. This observation was not unexpected and is consistent with general practice that the sheets should be clean before applying adhesive.

An important observation was that the lap shear specimens with voids in the seam parameters Nos. 11 and 12, showed only slightly different behavior in tension than that of the control *(Figure 2)*. The largest difference was a 30 percent decrease in the ultimate elongation, when round voids were present.

MEMBRANE MATERIAL SAMPLE NO. 2

For the four membrane materials in the study, sample No. 2 provided the most reproducible data for all application parameters. The relative standard deviation always was less than 7 percent in load at specimen failure *(Table 4)*. It was about 10 percent or less in ultimate elongation except for application parameter No. 5 which was about 15 percent less *(Table 4)*.

Figure 3 compares the load and ultimate elongation data.

A major observation is that the load at specimen failure for all application parameters generally was comparable to that of the control. Even for those specimens which were in the "as-received" condition with talc on the surface, or had dirt on their surfaces, parameters No. 4 and 5, little decrease in load at specimen failure was observed. For these two application parameters, the ultimate elongation decreased about 25 percent. For most of the other application parameters, the ultimate elongation was comparable to that of the control, except when voids were present.

As in the case of sample No. 1, voids, parameters Number 11 and 12, in the seam generally resulted in load and ultimate elongation values which were comparable to, or only slightly different than, those of the control. A 25 percent decrease in ultimate elongation was found for the specimens having rectangular voids *(Figure 3)*.

Membrane Material Sample No. 3

Test specimens for sample No. 3 gave acceptable reproducibility for the values of load and ultimate elongation at failure. In the case of load, the relative standard deviation generally was 10 percent or less *(Table 5)*. For ultimate elongation it was, except for parameter No. 3 and 12, 11 percent of less.

Again, the results of the lap shear specimens for sample No. 3 for all application parameters were comparable to that of the control. Application parameters such as surface condition, No. 4, 5 and 6, or voids, No. 11 and 12, which might be expected to decrease bond strength had little effect. For all parameters, the values of load at specimen failure were about the same or slightly greater than that of the control except for those specimens having 4- or 8-inch (100 or 200mm) laps. Here, loads were about 50 percent greater than that of the control.

With regard to ultimate elongation, values generally were about 10 to 15 percent less than that of the control. For application parameters 2 and 12, with 4-inch (100mm) laps and rectangular voids, the ultimate elongation increased and decreased about 40 percent.

A notable observation with membrane sample No. 3 was that the specimens having 8-inch (200mm) laps failed outside the seam. This was attributed to the membrane material properties. When seams fabricated from sample No. 3 were tested under tension, after the reinforcement ruptured considerable elongation occurred away from the lap as it was delaminating. This accounts for the relatively large, 200 percent elongations for sample No. 3. When the lap was 8 inches (200mm) long, the ultimate extension of the membrane material was exceeded before the lap totally delaminated. Partial delamination of the seam occurred before the material failed.

Membrane Material No. 4

Of the four samples tested, membrane material sample No. 4 generally produced the most scatter in results. In many cases, the relative standard deviation for the load at specimen failure was 25 percent or more *(Table 6)*. The relative standard deviation for ultimate elongation was, in many cases, 20 percent or more.

A major observation for membrane material No. 4 was that values for both load and ultimate elongation were about the same or greater than those of the control *(Figure 5)*. However, because of the relatively large scatter in the data, the differences between the results for control specimens and for other application parameters were not considered important. A large increase of both load and ultimate elongation was observed when the adhesive was applied to the heated membrane material *(Figure 5)*. As in the case for membrane sample No. 1 when heated, it may be that either improved wetting of the rubber surface occurred at the higher temperature or that a chemical reaction with marked temperature dependence took place during adhesive application or bond formation.

USE OF LAP SHEAR SPECIMENS IN SEAM EVALUATION

In this study few differences in load and ultimate elongation at specimen failure were observed between the control lap seam specimens and comparable specimens fabricated under various application conditions. This was particularly true of load values for samples No. 2 and 3 *(Figures 3 and 4)*. This was observed even though certain application parameters, such as surface contamination or voids in the seam, might have been expected to produce significant loss of strength. A few cases were found where surface contamination or voids produced lower strength, sample No. 1, application parameter 5 for example. However, no consistent trends were noticed. With regard to ultimate elongation, surface contamination and voids in the seam generally resulted in a decrease in this property. However, often the decrease was less than 15 percent of the value of the control.

Possible reasons for the application parameters having little effect on load and ultimate elongation might be an unexpected insensitivity of the adhesives to the surface condition of the rubber during application or an insensitivity of the lap shear test for detecting differences in bond strength. In the case of insensitivity of the adhesives to surface conditions during adhesive application, it is difficult to believe that at least some of the surface contaminants would not be detrimental to satisfactory bond formation.[11] Moreover, insensitivity of the adhesives to surface contaminants would not explain the observation that voids in the seams often had little effect on the strength. Good practice recommends that adhesives be applied to surfaces which are clean, dry, and free of contaminants. In a study of the practice of forming seams in EPDM membranes, Westley[6] concluded that surface preparation was a necessity and recommended that seams be formed only after cleaning the rubber surface. In addition, in discussing the effects of surface preparation, he showed that increased bond strength, as measured by peel or lap-shear tests, could be achieved through the use of a surface primer. In contrast, Dupuis[12] compared the ultimate strengths of lap seams fabricted from cleaned and uncleaned EPDM specimens and found little difference in strength when the specimens were tested at 70 and 150F (21 and 66C). His results were comparable to those found in this study. However, Dupuis did find that the uncleaned specimens were significantly weaker than the cleaned specimens when tested at −20F (−29C). He did not attempt to explain this observation. A possible reason may have been that the test was affected by the presence of moisture and water condensed on the specimens at the test temperature, resulting in lower measured strength.

With regard to surface contamination, a point not addressed in this study should be mentioned. Although the initial strengths of the specimens fabricated from cleaned and uncleaned rubber sheets may appear comparable as measured in a lap shear test, the effect of aging on cleaned and uncleaned specimens has not been evaluated. It may be that, depending upon the aging conditions, an uncleaned specimen has a significantly shorter service life than a cleaned specimen.

With regard to the sensitivity of the lap-shear test, the results of this study raise questions concerning the adequacy of the test procedure to detect differences in bond strength which might be introduced due to variations in application parameters. In particular, voids or disbond areas present in the lap seam did not produce a decrease in load at failure, although for some specimens there was a drop in ultimate elongation. A decrease in load might have been expected, since there was less bonded area. On a relative basis, it would seem that the lap shear test could be used to show these comparative effects. However, in discussions of this point with Venables[13] it was indicated that in testing bonds in adhesive-bonded, metal-to-metal specimens, the lap shear test has been observed to be less sensitive to detecting surface contaminants than other methods such as wedge or peel tests. It is suggested that a similar study be conducted on adhesive-bonded seams in single-ply membranes using a test method which might be more sensitive, such as the T-peel test.

No reasons for the insensitivity of the lap-shear test to detect voids or the effects of other application parameters are presented here. They should be the subject of further study. Such a study should investigate the relationship between the lap shear test and the factors affecting the performance of seams in service including failure modes and loading conditions. In addition, the effect of test parameters such as temperature, humidity, and rate of loading should also be investigated to determine whether they influence the sensitivity of tests regarding application conditions. Until further study is conducted, the use of lap shear tests for evaluating adhesive-bonded seams in single-ply membranes is questionable.

SUMMARY AND CONCLUSIONS

This study investigated the effect of application parameters on the adhesive bond in seams of rubber roofing membranes. Lap seams were formed under a variety of conditions using commercially available EPDM and neoprene rubbers. The application parameters investigated included lap length, surface contamination, moisture, temperature, and the presence of voids. Lap seam specimens were tested in tension and the load and ultimate elongation at specimen failure were compared as related to the application parameter.

The results indicated that, for the most part, little differences in load and ultimate elongation at specimen failure were observed for specimens fabricated under the different conditions. Observation that many seams having contaminated rubber surfaces or voids performed comparably to properly cleaned control specimens raises questions concerning the adequacy of the lap shear test procedure for detecting differences in bond strength caused by different application parameters.

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Sample No.	Type	Thickness in (mm)	Description
1	EPDM	0.050 (1.3)	Non-reinforced; no release agent on the surface
2	EPDM	0.060 (1.5)	Non-reinforced; talc release agent on the surface
3	EPDM	0.040 (1.0)	Reinforced; talc release agent on the surface
4	Neoprene	0.060 (1.5)	Non-reinforced; no release agent on the surface

Table 1 Vulcanized rubber membrane materials in the study

Parameter No.	Parameter Description
1	Control; 6 × 1.5-inch (150 × 38mm) lap-shear specimen having a 2-inch (50mm) lap; rubber was cleaned according to typical procedures.
2	4-inch (100mm) lap; cleaned as recommended for control.
3	8-inch (200mm) lap; cleaned as recommended for control.
4	As received; rubber was not cleaned before bond formation.
5	Dirty; dirt was brushed on the surface of the rubber before bond formation.
6	Wet; cleaned rubber was submerged in water without drying before bond formation.
7	Moisture at ambient temperature; cleaned rubber was subjected to 95 percent relative humidity at room temperature for 48 hours minimum immediately before bond formation.
8	Moisture at elevated temperature; cleaned rubber was subjected to 85 percent relative humidity at 122F (50C) for 48 hours minimum immediately before bond formation.
9	Cold temperature; cleaned rubber was cooled to about 41F (5C) before bond formation.
10	High temperature; cleaned rubber was heated to about 158F (70C) before bond formation.
11	Voids; a round void, 0.5-inch (13mm) in diameter, was incorporated in the center of the seam; rubber cleaned as recommended for control.
12	Voids; a rectangular void, 0.5 × 1-inch (13 × 25mm), was incorporated in the center of the seam; rubber cleaned as recommended for control.

Table 2 Application parameters included in the study

Parameter		Load at Failure, lbf/in				Load at Failure, N/mm				Ultimate Elongation, percent		
No.	Ave.	Range	σ[a]	RSD[b]	Ave.	Range	σ[a]	RSD[b]	Ave.	Range	σ[a]	RSD[b]
1	24.3	21.0-25.8	2.3	9.3	4.3	3.7- 4.5	0.40	9.3	137	120-150	13.5	9.9
2	17.9	17.0-18.8	0.76	4.3	3.1	3.0- 3.3	0.13	4.3	84	80- 85	2.5	3.0
3	23.2	20.0-27.3	3.1	13.4	4.1	3.5- 4.8	0.54	13.4	100	85-110	12.3	12.3
4	25.6	22.7-28.0	2.3	9.2	4.5	4.0- 4.9	0.40	9.2	131	120-150	13.2	10.0
5	14.0	12.3-15.5	1.3	9.3	2.5	2.2- 2.7	0.23	9.3	63	55- 65	5.0	8.0
6	30.9	27.3-38.0	5.2	16.9	5.4	4.8- 6.7	0.91	16.9	76	70- 85	6.3	8.3
7	21.9	17.5-24.8	3.3	15.2	3.8	3.1- 4.3	0.58	15.2	106	95-115	8.5	8.0
8	16.3	14.3-17.3	1.4	8.8	2.9	2.5- 3.0	0.25	8.8	--[c]			
9	26.8	25.2-28.7	1.7	6.4	4.7	4.4- 5.0	0.30	6.4	108	95-120	10.1	9.3
10	58.0	57.0-59.0	0.24	0.4	10.2	10.0-10.3	0.04	0.4	228	205-240	16.0	7.0
11	22.6	21.2-25.7	2.1	9.3	4.0	3.7- 4.5	0.37	9.3	95	85-105	7.5	7.9
12	29.3	26.0-32.3	2.6	9.0	5.1	4.6- 5.7	0.46	9.0	124	115-130	7.4	6.0

[a] o indicates standard deviation

[b] RSD indicated relative standard deviation.

[c] Ultimate elongation was not determined.

Table 3 Load and ultimate elongation at failure of lap-shear specimen for rubber sample No. 1 (EPDM)

Parameter		Load at Failure, lbf/in				Load at Failure, N/mm				Ultimate Elongation, percent		
No.	Ave.	Range	σ[a]	RSD[b]	Ave.	Range	σ[a]	RSD[b]	Ave.	Range	σ[a]	RSD[b]
1	13.0	12.3-13.8	0.84	6.4	2.3	2.2-2.4	0.15	6.4	105	90-115	10.7	10.2
2	14.9	14.3-15.8	0.67	4.5	2.6	2.5-2.8	0.12	4.5	114	105-120	6.3	5.5
3	14.6	14.3-15.0	0.29	2.0	2.6	2.5-2.6	0.05	2.0	106	105-110	4.8	4.5
4	12.5	11.8-12.7	0.45	3.6	2.2	2.1-2.2	0.08	3.6	80	-	0	0
5	12.6	11.7-13.2	0.75	6.0	2.2	2.0-2.3	0.13	6.0	83	65-100	14.4	17.5
6	15.3	15.0-16.0	0.48	3.1	2.7	2.6-2.8	0.08	3.1	113	110-115	2.9	2.6
7	16.0	15.8-16.3	0.25	1.6	2.8	2.8-2.9	0.04	1.6	100	95-105	4.1	4.1
8	14.8	14.5-14.8	0.16	1.1	2.6	2.5-2.6	0.03	1.1	93	90- 95	2.9	3.1
9	15.3	14.5-15.7	0.57	3.7	2.7	2.5-2.7	0.10	3.7	114	110-120	3.0	2.6
10	14.6	14.0-15.0	0.42	2.9	2.6	2.5-2.6	0.07	2.9	108	105-115	4.7	4.4
11	13.0	11.7-13.8	0.90	6.9	2.3	2.0-2.4	0.16	6.9	92	80-100	8.5	9.3
12	11.7	11.3-12.0	0.31	2.7	2.0	2.0-2.1	0.05	2.7	78	75- 85	5.4	6.9

[a] σ indicated standard deviation

[b] RSD indicates relative standard deviation.

Table 4 Load and ultimate elongation at failure of lap-shear specimen for rubber sample No. 2 (EPDM)

Parameter		Load at Failure, lbf/in				Load at Failure, N/mm				Ultimate Elongation, percent		
No.	Ave.	Range	σ[a]	RSD[b]	Ave.	Range	σ[a]	RSD[b]	Ave.	Range	σ[a]	RSD[b]
1	17.2	16.0-18.3	1.0	6.0	3.0	2.8-3.2	0.18	6.0	201	195-215	9.5	4.7
2	26.0	24.7-28.0	1.4	5.5	4.6	4.3-4.9	0.25	5.5	239	225-255	13.8	5.8
3[c]	26.8	25.3-29.7	2.1	7.7	4.7	4.4-5.2	0.37	7.7	179	125-260	60.9	34.1
4	18.2	16.7-21.0	2.0	10.8	3.2	2.9-3.7	0.35	10.8	169	145-190	18.7	11.5
5	19.3	18.0-21.3	1.6	8.4	3.4	3.2-3.7	0.28	8.4	186	175-200	11.1	6.0
6	19.6	17.7-21.3	1.7	8.7	3.4	3.1-3.7	0.30	8.7	178	155-195	18.5	10.4
7	17.5	16.3-19.0	1.4	7.9	3.1	2.9-3.3	0.25	7.9	186	170-210	18.0	9.7
8	16.7	16.3-17.0	0.27	1.7	2.9	2.9-3.0	0.05	1.7	174	160-190	12.5	7.2
9	20.2	19.3-21.3	0.83	4.1	3.5	3.4-3.7	0.15	4.1	185	175-195	8.2	4.4
10	20.3	19.3-21.3	0.97	4.8	3.6	3.4-3.7	0.17	4.8	182	165-205	20.6	11.3
11	20.1	19.0-21.3	0.97	4.9	3.5	3.3-3.7	0.17	4.9	177	155-200	18.6	10.5
12	19.8	18.3-21.7	1.6	7.9	3.5	3.2-3.8	0.28	7.9	154	90-190	45.6	29.6

[a] σ indicates standard deviation

[b] RSD indicates relative standard deviation.

[c] Specimens failed away from the seam.

Table 5 Load and ultimate elongation at failure of lap-shear specimen for rubber sample No. 3 (EPDM)

Parameter		Load at Failure, lbf/in				Load at Failure, N/mm				Ultimate Elongation, percent		
No.	Ave.	Range	σ[a]	RSD[b]	Ave.	Range	σ[a]	RSD[b]	Ave.	Range	σ[a]	RSD[b]
1	13.4	12.5-14.0	0.68	5.1	2.3	2.2- 2.5	0.12	5.1	62	60- 65	2.1	3.3
2	19.1	16.7-22.7	2.6	13.4	3.3	2.9- 4.0	0.46	13.4	99	85-105	9.5	9.6
3	15.0	12.7-16.2	1.6	10.8	2.6	2.2- 2.8	0.28	10.8	85	75- 95	9.1	10.7
4	13.0	11.7-14.0	0.96	7.4	2.3	2.0- 2.5	0.17	7.4	64	55- 70	7.1	11.1
5	20.1	15.3-22.3	3.3	16.2	3.5	2.7- 3.9	0.58	16.2	93	60-110	22.5	24.4
6	10.8	9.3-14.3	2.4	22.2	1.9	1.6- 2.5	4.2	22.2	49	40- 65	11.1	22.7
7	20.6	15.2-27.2	5.0	24.2	3.6	2.7- 4.8	0.88	24.2	103	75-130	22.9	22.0
8	14.8	13.5-15.3	0.87	5.9	2.6	2.4- 2.7	0.15	5.9	70	60- 75	7.1	10.1
9	20.2	18.8-21.7	1.4	6.9	3.5	3.3- 3.8	0.25	6.9	102	95-110	6.4	6.2
10	58.5	28.7-80.0	22.8	39.0	10.2	5.0-14.0	4.0	39.0	227	115-315	87.7	36.6
11	14.6	9.3-28.0	9.0	62.0	2.6	1.6- 4.9	1.6	62.0	60	30-120	41.8	70.3
12[c]	23.7	17.7-35.0	9.8	41.5	4.2	3.1- 6.1	1.7	41.5	119	95-170	43.9	36.8

[a] σ indicates standard deviation

[b] RSD indicated relative standard deviation.

[c] Results for three specimens only.

Table 6 Load and ultimate elongation at specimen of lap-shear specimen for rubber sample No. 4 (Neoprene)

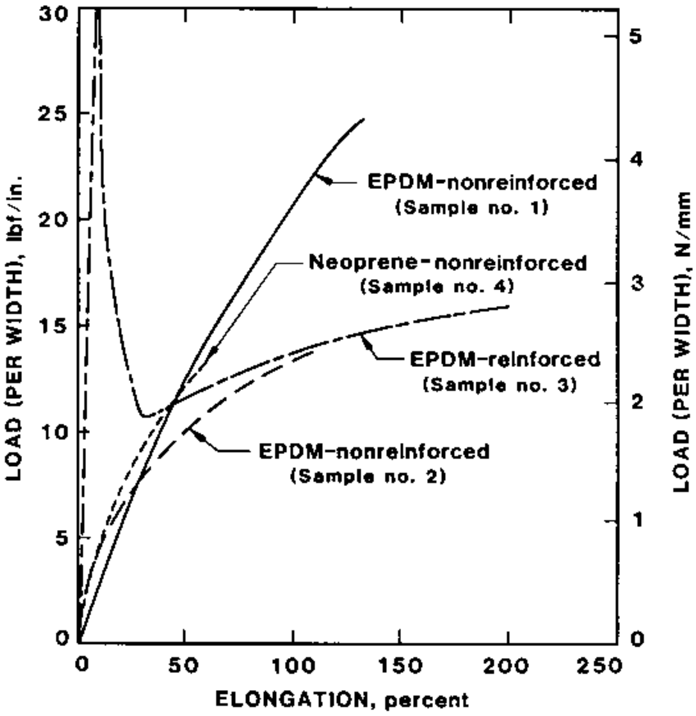

Figure 1 *Load-elongation curves of lap seam control specimens tested in tension*

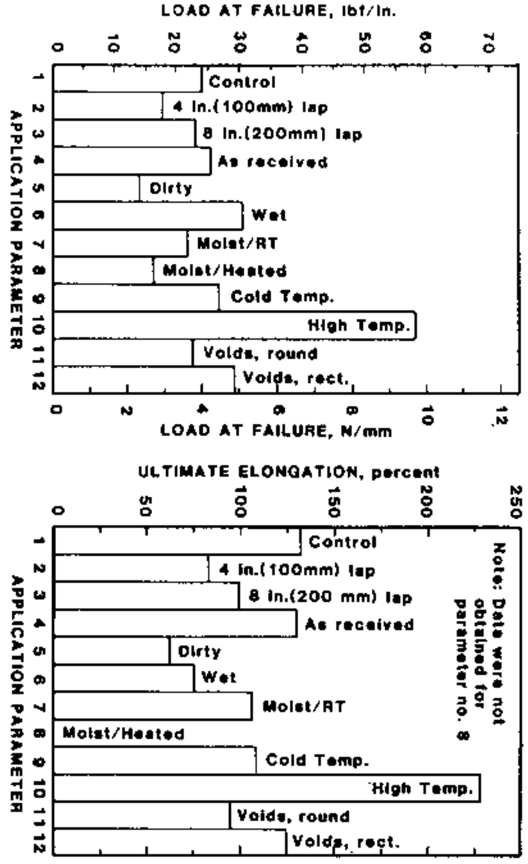

Figure 2 *A comparison of the load and ultimate elongation at specimen failure as related to application parameters for membrane sample No. 1*

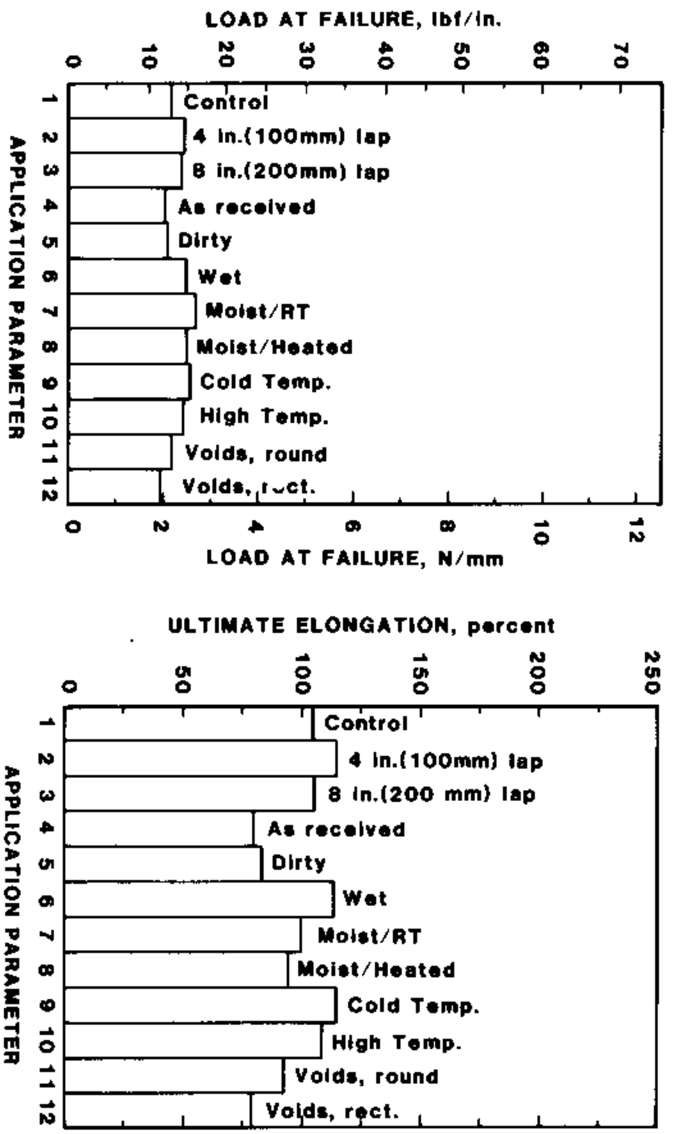

Figure 3 *A comparison of the load and ultimate elongation at specimen failure as related to application parameters for membrane sample No. 2*

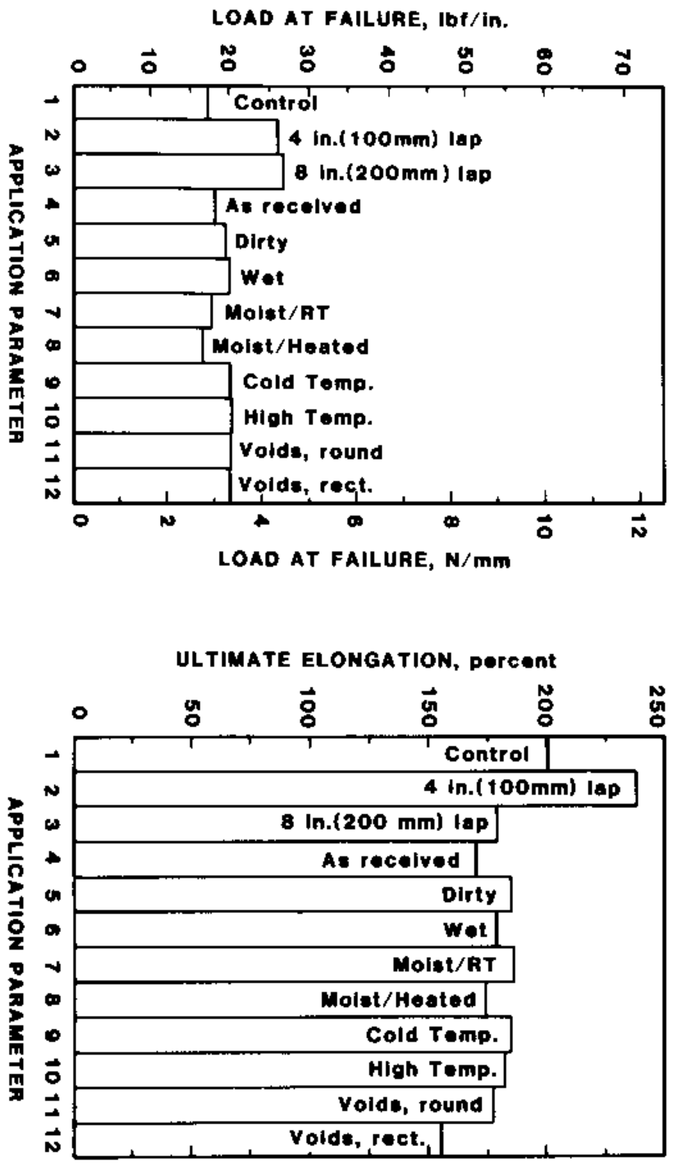

Figure 4 A comparison of the load and ultimate elongation at specimen failure as related to application parameters for membrane sample No. 3

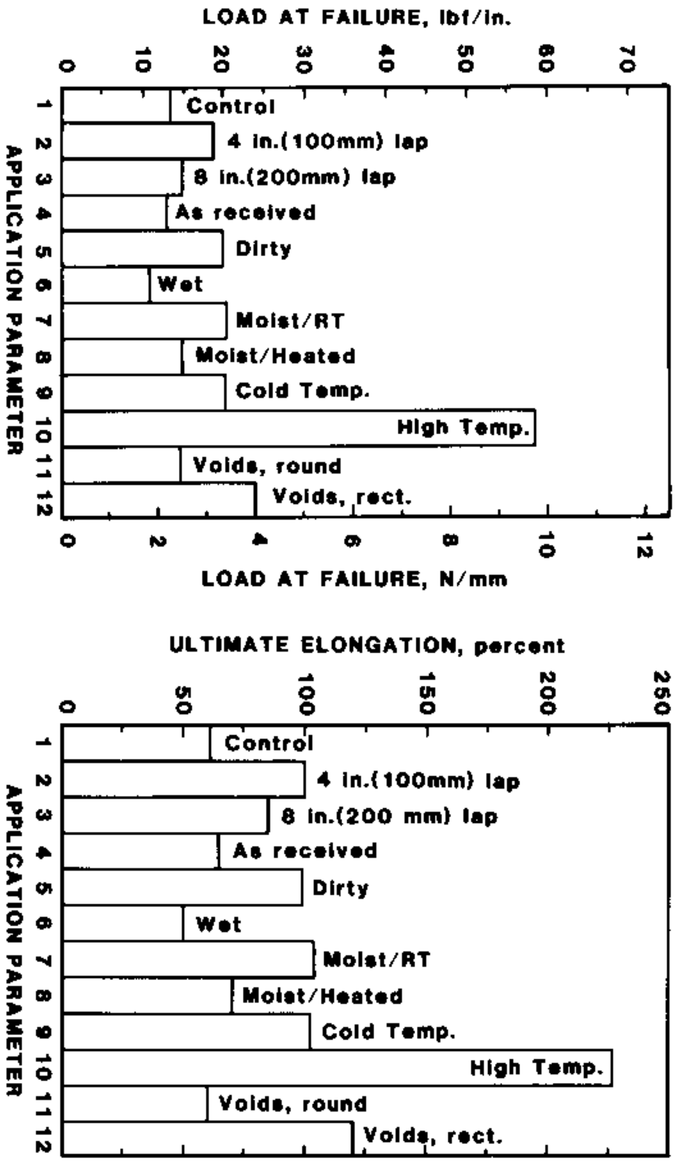

Figure 5 A comparison of the load and ultimate elongation at specimen failure as related to application parameters for membrane sample No. 4