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Welding of Thermoplastic Roofing Membranes Subjected to Different Conditioning Procedures

ABSTRACT: The use of thermoplastic roofing membranes has grown dramatically over the past years. This has occurred for a number of reasons including the proven track record of some products, the move to light colored "cool" materials, and the variety of systems available. A key benefit of thermoplastic membranes is the ability to hot air weld their seams, creating a permanent seal. As these single-ply membranes are installed in a one-ply configuration, a properly executed seam is critical to their long-term performance. Welding properties of membranes from five different manufacturers of thermoplastics: two polyvinyl chloride (PVC), two thermoplastic olefins (TPO), and one KEE (ketone ethylene ester) were studied. All materials were welded at twelve different combinations of welding temperature and speed. Each of these "welding windows" was completed with material as received, after 4 days immersed in water and after 30 days of exposure to severe soiling. Finished welds were assessed by peel testing in a tensile test apparatus. Differences in welding properties of specific materials and the generic types of products were evaluated, including sensitivity to changes in weld parameters, the effectiveness of manufacturer recommended cleaning/seam preparation, as well as the impact of the conditioning processes on weld quality. Integrating a previous study by others, a weld safety factor concept was developed which is a useful metric for assessing weld quality. This work demonstrated the need for clear, product specific welding guidelines for both new materials and for roof membranes exposed to the elements so as to ensure a proper weld.

KEYWORDS: KEE, membrane seams, membrane welding, PVC, roofing, single ply, thermoplastic membranes, TPO

Introduction

Thermoplastic single-ply roof membranes have been around for more than 40 years. They were introduced in Europe in the 1960s and in North America in the 1970s. In the 1980s and early 1990s they enjoyed steady if unspectacular growth. Throughout the 1990s and the early 2000s, there has been a significant shift in market share among product categories in the low slope commercial roofing market. According to the most recent (May 2007) Single Ply Roofing Institute (SPRI) statistics, thermoplastic membranes now comprise the largest share (36 %) of the single-ply commercial roofing industry.

This growth has been the result of a number of factors, including an increasing environmental awareness. Reflective thermoplastic membranes have been found to reduce cooling costs and to contribute to a reduction in the "Urban Heat Island Effect." This awareness has led to the creation of a number of both voluntary and legislative measures to increase the use of reflective roofing materials, such as the Energy Star program and California's Title 24 energy code. Such growth would, however, have been highly unlikely without the long-term record of proven performance of a number of thermoplastic products. This performance was due in part to the formulation of these products, but equally importantly was the reliability of their thermally fused seams.

Single-ply membranes do not provide for any redundancy. A less than perfect single-ply seam almost inevitability leads to a leak. Since their introduction about four decades ago, thermoplastic membranes have been seamed by welding adjacent sheets together using either solvent or hot air. The use of solvents was abandoned about 15 to 20 years ago due to health, safety, performance, and environmental reasons. Although there have been few, if any, changes in the fundamental technology of hot air welding, new generations of materials such as thermoplastic olefins (TPO) has created new challenges for contractors

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installing these materials. This study was conducted to compare the welding properties of a sampling of commercially available thermoplastic roofing membranes.

Experimental Program

Thermoplastic membranes produced by five different manufacturers were acquired: two thermoplastic polyolefins (TPO), one ketone ethylene ester (KEE) modified polyvinyl chloride, and two "traditional" polyvinyl chloride (PVC) membranes. The original intent was to test 1.5 mm (60 mil), polyester reinforced samples of all products. However, only 0.9 mm (36 mil) KEE could be sourced. Although thinner than the other samples it was felt that the material should be tested nonetheless to ensure all three categories of thermoplastic roofing membranes were represented in the study. The samples were labeled TPO 1, TPO 2, PVC E (KEE material), PVC 1, and PVC 2. All products in the main study were polyester reinforced. Products TPO 1, PVC 1 and PVC 2 had smooth surfaces, both top and bottom. The scrim telegraphed through both surfaces of membranes TPO 2 (significantly) and PVC E (moderately) providing a texture to both sheets.

Membranes were cut into 20-cm (8-in.) wide, by 914-cm (30-in.) long strips. Each material was subjected to two conditioning procedures. Samples from one set of materials were loosely rolled and fully submerged in water for a period of four days at room temperature. An additional set of samples was laid outdoors, and covered with a mixture of 136 kg (300 lb) of thoroughly mixed organic topsoil, stone dust, and fine sand. The soiling compound was broomed across the membrane samples and then rolled over numerous times with a weighted lawn roller. The soil was left in place on the membrane samples for a 30-day period during the month of July 2005 (average mean temperature: 23 °C (74 °F), total precipitation 8.56 cm (3.37 in.)).

The conditioning procedures are intended to assist in assessing the degree to which products maintain their weldability when subjected to conditions common to rooftops: moisture and soiling. The conditioning procedures are intended to simulate severe exposure to moisture; for example, as a result of improper material storage on site, material that is subjected to continuous ponding over time, or exposure over time to airborne soil depositions on low slope roofs.

Welding Trials

Samples were welded as received, after water immersion and after soiling

All 15 sets of samples (five materials, three conditions) were welded for each combination of three welding speeds, 1.5, 2.0, 2.5 m/min (4.9, 6.5, 8.2 ft/min) and four temperatures 350, 400, 450, 500 °C (662, 752, 842, 932 °F). A total of twelve weld conditions were carried out per sample set.

At each temperature, one pair of samples, overlapped 76 mm (3 in.), was used for all three welding speeds as shown in Fig. 1, starting 1.5 m/min (4.9 ft/min) at one end, 2.0 m/min (6.5 ft/min) in the middle, and 2.5 m/min (8.2 ft/min) at the far end of the test strips.

Water was allowed to drip from the submerged samples as they were removed from the baths. The samples were then unrolled and both the top surface and the underside of each sample were dried with a cloth until all visible moisture was removed. The samples were then welded. Typically welding occurred within 15 minutes of drying. For products with a factory-sealed edge, the sealed edge was used as the top sheet in welding the samples which had been immersed in water.

The soil was removed from the outdoor test area with a broom, before the samples were taken inside to the test area. As outlined in Table 1, soiled samples were cleaned according to procedures outlined in each membrane manufacturer's product literature prior to welding. Every effort possible was made to return the membranes to their original appearance using the prescribed procedures. Welding was conducted within the same day as the cleaning processes.

Temperatures and weld speed were read from the automatic welder's digital control panel display in metric units. In previous work [1], it was noted that the substrate upon which the thermoplastic membranes were welded (e.g., thermal insulation or concrete) did not impact the final experimental results. For convenience and consistency, all samples were welded over a concrete substrate.

During the testing program significant discussion about weld width ensued. Many manufacturers require a minimum of a 37-mm (1.5-in.) wide weld. Factory Mutual system approvals typically note a

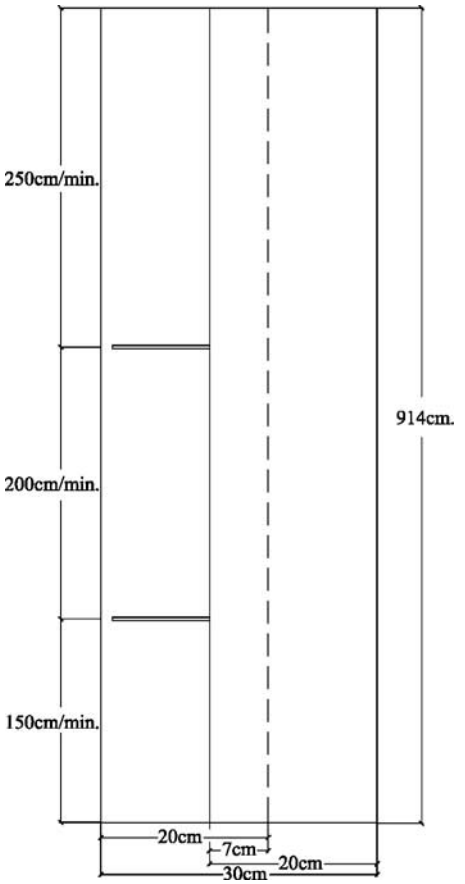

FIG. 1—*Material layout for seam welding.*

minimum of 37-mm (1.5-in.) wide welds. Many inspectors, both manufacturers' representatives and third party consultants, consider anything narrower to be unacceptable, and they will typically insist on such seams being stripped in. It was decided to conduct a small test program by preparing two sets of samples (one glass mat reinforced and one polyester reinforced) with precisely controlled weld widths for T Peel testing. Samples were peeled at 180° on a Physical Testing Equipment Services Model J Tester, at a speed of 111 mm/min (4.5-in./min). This was followed by a full scale 366 cm by 732 cm (12 ft by 24 ft) uplift test at Factory Mutual Engineering with 13-mm (0.5-in.) wide welded seams in the test panel.

TABLE 1—*Cleaning procedures used to remove soiling.*

Product	Cleaning Procedures
TPO 1	Water and rag
	Simple Green and floor brush
	Water rinse
	Acetone with cotton rags
TPO 2	Water and Simple Green
	3M scrub pad with manufacturer's solvent (xylene)
	Cotton rag with solvent
PVC E	Water and rag
	Cotton rag with acetone
PVC 1	Water and rag
	Cotton rag with acetone
PVC 2	Water and rag
	Rag with methyl ethyl ketone (MEK)

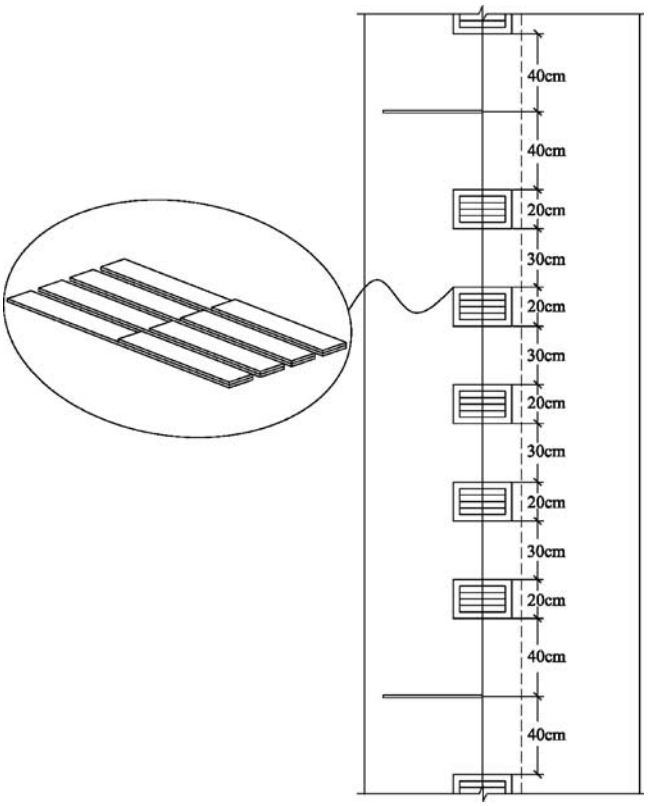

FIG. 2—*Sample removal.*

Sample Testing

As shown in Fig. 2, five 200-mm (8-in.) wide samples were removed from each combination of material, conditioning procedure, and weld parameters. Using a metal template centered on each sample, five 255 mm (1 in.) strips were taken. One sample was taken from each set for tensile testing, for a total of five samples per combination. T peel tests were conducted on a United Tensile Tester according to ASTM D 1876-95. All data noted in Table 2 represent the average of five T peels; standard deviations are given in the Appendix. Tensile data were recorded in pound-force and converted to S.I. units.

Peel Test Results

The peel strength of the "as received" samples for both TPO materials varied little with changes to welding temperatures and speeds. For TPO 1, seam strength varied from a low of 10.8 kN/m (61.8 lbf/in.), to a high of 12.2 kN/m (69.9 lbf/in.), across the entire spectrum of conditions. TPO 2 exhibited the lowest magnitude of variation of all materials, with all peels measured within a narrow band of −2 % to +4 % around 6.8 kN/m (39.0 lbf/in.), regardless of weld conditions. TPO 2's seam strength was, however, only about 60 % of that of TPO 1 at any given set of conditions. According to published literature for both products, TPO 2's breaking strength is only 5 % less than that of TPO 1. Clearly the differences observed are a reflection of the products' relative seam strength, rather than simply sheet strength.

PVC 1 exhibited dramatic differences in results with changing weld parameters. Only a nominal weld was achieved at 350°C (662 °F), regardless of the speed. At 400°C (752 °F), although strong welds were realized at 1.5 m/min, an increase of 0.5 m/min in speed resulted in a drop of 73 % in weld strength, and a further increase in speed resulted in an additional 32 % loss. Results were more consistent at the higher temperatures with values of approximately 12.2 kN/m (70.0 lbf/in.) and greater achieved at all conditions. PVC 2 exhibited much less variation than PVC 1 across the various conditions. It is interesting to note, however, that whereas PVC 1 weld strength appeared to increase with increasing temperature, the trend was reversed for PVC 2, with the best weld strengths occurring at the lower temperatures. PVC E exhibited the least variation in seam strength among the three PVC samples. The maximum strength of the PVC E welds was, however, only slightly greater than half the peak seam strength of PVC 1 and PVC 2.

TABLE 2—*Peel test results for all conditioning procedures and welding parameters.*

Welding Temp. T (°C)	Weld Speed m/min	TPO 1 lbf/in.	TPO 1 kN/m	TPO 2 lbf/in.	TPO 2 kN/m	PVC 1 lbf/in.	PVC 1 kN/m	PVC E lbf/in.	PVC E kN/m	PVC 2 lbf/in.	PVC 2 kN/m
As Received											
350	1.5	64.1	11.2	38.1	6.7	12.2	2.1	28.2	4.9	66.4	11.6
350	2	64.8	11.3	38.9	6.8	4.4	0.8	31.4	5.5	75.1	13.1
350	2.5	65.9	11.5	39.5	6.9	3.7	0.6	28.5	5.0	69.3	12.1
400	1.5	65.5	11.5	39.4	6.9	68.5	12.0	32.6	5.7	64.5	11.3
400	2	68.7	12.0	39.8	7.0	18.3	3.2	31.5	5.5	62.0	10.9
400	2.5	69.9	12.2	39.8	7.0	12.4	2.2	34.5	6.0	68.4	12.0
450	1.5	61.8	10.8	40.0	7.0	69.9	12.2	38.6	6.8	58.1	10.2
450	2	67.1	11.7	40.5	7.1	71.9	12.6	34.9	6.1	63.5	11.1
450	2.5	68.8	12.0	39.6	6.9	69.4	12.1	25.1	4.4	65.4	11.4
500	1.5	64.6	11.3	40.0	7.0	69.6	12.2	38.2	6.7	65.5	11.5
500	2	69.4	12.1	40.3	7.1	77.0	13.5	41.2	7.2	53.1	9.3
500	2.5	67.0	11.7	39.9	7.0	69.3	12.1	32.1	5.6	56.1	9.8
Water Conditioning											
350	1.5	53.0	9.3	27.2	4.8	39.9	7.0	29.5	5.2	68.3	12.0
350	2	51.1	8.9	19.4	3.4	27.7	4.8	28.1	4.9	64.7	11.3
350	2.5	40.4	7.1	13.2	2.3	11.2	2.0	23.7	4.1	50.8	8.9
400	1.5	51.6	9.0	41.3	7.2	59.9	10.5	25.7	4.5	51.5	9.0
400	2	52.7	9.2	40.8	7.1	34.8	6.1	21.6	3.8	51.5	9.0
400	2.5	55.3	9.7	21.1	3.7	29.6	5.2	24.9	4.4	64.4	11.3
450	1.5	49.9	8.7	41.7	7.3	39.9	7.0	26.2	4.6	37.6	6.6
450	2	51.4	9.0	44.4	7.8	49.9	8.7	22.5	3.9	45.7	8.0
450	2.5	45.5	8.0	36.3	6.4	44.9	7.9	23.5	4.1	46.0	8.1
500	1.5	44.1	7.7	39.5	6.9	27.1	4.7	25.7	4.5	53.6	9.4
500	2	53.3	9.3	45.4	7.9	46.2	8.1	29.7	5.2	37.0	6.5
500	2.5	46.9	8.2	40.6	7.1	46.8	8.2	25.6	4.5	36.9	6.5
Soil Conditioning											
350	1.5	52.1	9.1	38.0	6.7	60.0	10.5	23.0	4.0	61.7	10.8
350	2	55.3	9.7	34.3	6.0	55.8	9.8	28.6	5.0	65.9	11.5
350	2.5	42.4	7.4	23.7	4.1	40.9	7.2	26.2	4.6	63.7	11.1
400	1.5	52.1	9.1	33.6	5.9	44.5	7.8	23.3	4.1	70.9	12.4
400	2	54.3	9.5	32.9	5.8	37.5	6.6	24.9	4.4	69.1	12.1
400	2.5	44.4	7.8	31.6	5.5	43.1	7.5	24.8	4.3	72.2	12.6
450	1.5	46.2	8.1	38.6	6.8	55.8	9.8	27.7	4.8	64.1	11.2
450	2	48.4	8.5	31.8	5.6	52.1	9.1	21.8	3.8	66.2	11.6
450	2.5	43.0	7.5	25.8	4.5	49.1	8.6	23.8	4.2	70.8	12.4
500	1.5	37.0	6.5	35.2	6.2	58.5	10.2	30.3	5.3	67.5	11.8
500	2	51.6	9.0	37.6	6.6	75.4	13.2	24.3	4.3	69.3	12.1
500	2.5	52.8	9.2	36.0	6.3	77.0	13.5	26.7	4.7	74.7	13.1

Water immersion tended to result in a reduction in weld strength, with a few exceptions. Generally when materials absorb water the application of the heat required for hot air welding results in the vaporization of absorbed moisture, which results in the formation of blisters within the weld, resulting in a reduction of weld strength. This was generally the case for TPO 1, PVC E, and PVC 2, with all three products losing up to 40 % of their original weld strength at the various parameters. TPO 2 and PVC 1 were exceptions. At 400, 450, and 500°C (752, 842, and 932 °F) TPO 2 tended to have equal or better weld strengths than it did as received. PVC 1 also had equal or better weld strengths after water immersion compared to the unconditioned values, which were, however, much lower than most of the other products. At the higher temperatures, loss of weld strength ranged from 30 % to better than 60 %.

After soiling and seam preparation, PVC 2 seam strength was restored to better than 90 % of its

TABLE 3—*Small scale peel tests at various weld widths.*

Membrane	Weld Width (in.)	Weld Width (cm)	Peel (lbf)	Peel kN/m
60 mil, PVC, glass mat	0.5	1.3	49	8.5
60 mil, PVC, glass mat	1.0	2.5	46	9.0
60 mil, PVC, glass mat	1.5	3.8	50	8.7
48 mil PVC, polyester	0.5	1.3	50	8.7
48 mil PVC, polyester	1.25	3.1	49	8.5
48 mil PVC, polyester	1.5	3.8	54	9.3

original values in all conditions, reaching 100 % retention at all but the lowest weld temperature. TPO 1 seems in general to retain less of its original peel strengths after soiling and cleaning than after water immersion. This may suggest that the recommended cleaning procedure for this product could be improved upon. PVC 1 tends towards almost complete restoration of peel strength after soiling and cleaning with the exception of at 450°C.

The results of the small scale peel tests at various weld widths are shown in Table 3. As can be seen, the difference in strength between the narrowest and the widest seam was only 2 % for the 15 mm (60 mil) glass mat supported membrane. The 13-mm (0.5-in.) wide seam was stronger than the 25-mm (1-in.) wide seam. For the 12 mm (48 mil) polyester sheet the gap was a little greater at 8 %, but the trends were similar. Tripling the width of the weld appears to have only minimal effect on the seam strength of these products.

The second test involved assembling a test panel using the same polyester reinforced PVC membrane used for lab peel tests for simulated uplift testing at Factory Mutual Engineering. The manufacturer's mechanically attached listings were at the time all based on a 38 mm (1.5 in.) minimum seam width. The 3 m (10 ft) membrane, fastened 152 mm (6 in.) o.c. failed at 120 lbf/in.^{2} as a result of fastener pull-out, a result comparable to that achieved with a 38 mm (1.5 in.) weld in previous approval testing. As a result of this test, FM modified the manufacturer's listings to include the following:

> All currently approved single-welded {*Manufacturer's name*} mechanically fastened roof cover constructions with a maximum Class 1-105 rating are approved with a minimum 0.5 in. (13 mm) wide heat weld placed on the outside edge of the lap.

Within the context of the minimal amount of data generated, it appears that for practical purposes, there is little, if any, difference in performance between a properly constructed 13-mm (0.5-in.) and a 38-mm (1.5-in.) wide weld.

Discussion

These sets of data highlight a key challenge in interpreting and applying the knowledge gained from the results. It is very difficult to establish trends along the speed and temperature continuums, or both, for any given material. Trends are inconsistent both between materials in a generic group, and within each specific product.

Although useful, the absolute data are of limited value in assessing and comparing the results. An alternative approach to absolute data and relative data (% retention of original) could be beneficial. The absolute peel test data must be viewed in a performance context to be of practical use. Failure modes during peel tests can be divided into two categories: adhesive and cohesive, with failure occurring within the seam and within the membrane material, respectively. The adhesive/cohesive terminology is not strictly correct as applied to welded or fused seams. However, it has traditionally been used throughout the single-ply roofing industry, and it is well understood by manufacturer's field technical personnel, installation contractors, and researchers. Thermoplastic membrane manufacturers call for peel tests to be done manually on seams throughout the installation phase of the roofing materials. Seams that fail adhesively are deemed to be unacceptable and typically must be patched or stripped in as a precondition to the warranty being issued. Simmons et al. [1] found that adhesive failure was typically observed when seam strength was found to be 4.5 kN/m (26 lbf/in.) or less, whereas cohesive failure typically was observed in samples with seam strengths greater than this value. In the present study, 26 seams were found to have

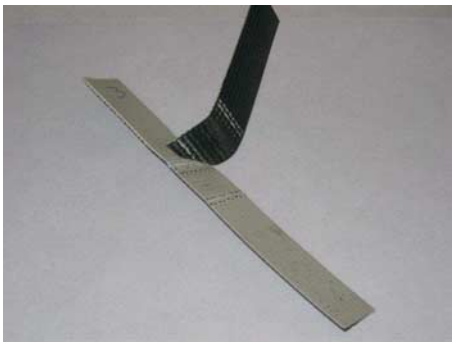

FIG. 3—*TPO 2, soiled, 350°C, 2 m/min, 5.9 kN/m (34.0 lbf/in.).*

failed at that value or lower. Examining the tested samples, it was found that 25 of the 26 had failed adhesively, validating Simmons et al.'s [1] observation.

One must be cautious, however, in the use of this concept. Relying exclusively on simple numerical values can in some instances prove misleading. For example TPO 2 (soiled, 350°C, 2 m/min), achieved a weld strength of 5.9 kN/m (34 lbf/in.), cohesive failure by this definition. However, examining the sample (Fig. 3), one can see that the area of fused polymer holding the welds together is minuscule, and that the greatest part of the seam has failed adhesively. Such a seam would not be likely to be able to withstand the stresses imposed within a lap attached system. Blistering was also observed in a number of the seams after water immersion. Although high peel strengths were still measured, such seams may deteriorate prematurely due to freeze thaw cycling or other mechanisms in the field. Therefore it is important to remember that acceptable peel strength and weld continuity are equally important in assessing a seam on a roof.

This value does nonetheless provide us with a basis for calculating a weld safety factor to evaluate and assess seam quality at various conditions, or to compare the welds of various materials, at least under experimental conditions. The safety factor (*SF*) will be defined as:

$$SF = \frac{T\ Peel(\text{lbf/in.}) - 26}{26}$$

where *T Peel* is the ultimate tensile strength of the seam, measured in lbf/in.

Safety factor data are compiled in Table 4.

As received TPO 1 and PVC 2 provide safety factors in excess of 0.4 in all cases, with most conditions yielding safety factors well in excess of 1.0 (i.e., 100 % or double the defined threshold value). TPO 2 and PVC E represent the other end of the spectrum providing little room for error at any set of parameters. It would appear that the telegraphing of the scrim through the surfaces of these materials is a detriment to achieving high weld strengths. In the case of PVC E, the lesser thickness of the available polymer to achieve a weld very likely compounds the challenge of trying to achieve a strong weld.

For materials that had been immersed in water TPO 1 and PVC 2 appear to provide the greatest overall degree of safety, albeit in inverse fashion. PVC 2 allows for a higher level of safety at the more moderate temperatures, whereas TPO 1 provides it at the higher welding temperatures. TPO 2 achieves nominal safety factors at higher temperatures as does PVC 1, except at the lower welding speeds. Based on the data generated in this test program, PVC E provides no room for error. Although four days of immersion may be severe, the results are troubling when one considers the material was thoroughly surface dried, and welding was completed under highly controlled conditions. These results may be a predictor of potential welding problems for this product when exposed to significant moisture effects in the field.

After soiling and cleaning, PVC 2 provides the greatest margin of safety, at all conditions, with safety factors ranging from 1.4 to 1.9. PVC 2 achieves safety factors equal to or better than the "as received condition." Although TPO 1 provides for good safety factors, despite an aggressive, multi-step cleaning process, there is clearly a reduction from the values achieved "as received." TPO 2 suffers from a modest degree of loss in safety factor, although at such low levels for new material, any reduction in safety margin could be critical in practice. The results for PVC E are quite similar to those evaluated after water immersion. Once again, there is no margin of safety in welding this product.

TABLE 4—*Safety factors evaluated for all conditioning procedures and welding parameters.*

Welding Temp. T (°C)	Weld Speed m/min	TPO 1 Safety Factor	TPO 2 Safety Factor	PVC 1 Safety Factor	PVC E Safety Factor	PVC 2 Safety Factor
As Received						
350	1.5	1.5	0.5	−0.5	0.1	1.6
350	2	1.5	0.5	−0.8	0.2	1.9
350	2.5	1.5	0.5	−0.9	0.1	1.7
400	1.5	1.5	0.5	1.6	0.3	1.5
400	2	1.6	0.5	−0.3	0.2	1.4
400	2.5	1.7	0.5	−0.5	0.3	1.6
450	1.5	1.4	0.5	1.7	0.5	1.2
450	2	1.6	0.6	1.8	0.3	1.4
450	2.5	1.6	0.5	1.7	0.0	1.5
500	1.5	1.5	0.5	1.7	0.5	1.5
500	2	1.7	0.6	2.0	0.6	1.0
500	2.5	1.6	0.5	1.7	0.2	1.2
Water Conditioning						
350	1.5	1.0	0.0	0.5	0.1	1.6
350	2	1.0	−0.3	0.1	0.1	1.5
350	2.5	0.6	−0.5	−0.6	−0.1	1.0
400	1.5	1.0	0.6	1.3	0.0	1.0
400	2	1.0	0.6	0.3	−0.2	1.0
400	2.5	1.1	−0.2	0.1	0.0	1.5
450	1.5	0.9	0.6	0.5	0.0	0.4
450	2	1.0	0.7	0.9	−0.1	0.8
450	2.5	0.8	0.4	0.7	−0.1	0.8
500	1.5	0.7	0.5	0.0	0.0	1.1
500	2	1.1	0.7	0.8	0.1	0.4
500	2.5	0.8	0.6	0.8	0.0	0.4
Soil Conditioning						
350	1.5	1.0	0.5	1.3	−0.1	1.4
350	2	1.1	0.3	1.1	0.1	1.5
350	2.5	0.6	−0.1	0.6	0.0	1.5
400	1.5	1.0	0.3	0.7	−0.1	1.7
400	2	1.1	0.3	0.4	0.0	1.7
400	2.5	0.7	0.2	0.7	0.0	1.8
450	1.5	0.8	0.5	1.1	0.1	1.5
450	2	0.9	0.2	1.0	−0.2	1.5
450	2.5	0.7	0.0	0.9	−0.1	1.7
500	1.5	0.4	0.4	1.3	0.2	1.6
500	2	1.0	0.4	1.9	−0.1	1.7
500	2.5	1.0	0.4	2.0	0.0	1.9

Conclusions

The study demonstrated that the welding properties of thermoplastic membranes vary significantly, even within a given generic group. The ideal conditions for achieving the strongest weld are very different for every product. In many instances increasing or decreasing weld speed or temperature even one level can have a dramatic impact on seam strength. Even under ideal conditions, some products provide for little, if any margin of safety as defined in this paper. If anything, the threshold chosen as a base value should probably be even more conservative to account for situations such as the one highlighted, where although the numerical value was met, from a practical perspective the sample would not be considered to have failed cohesively during a field investigation.

Further work, done in parallel with field surveys, would be required to establish a minimum safety

factor that would allow for the various field variables in defining welding parameters for each product, under different conditions. However, in evaluating the data generated and considering the practical implications, one must keep in mind the relative contexts of the study and the field in which welding is carried out in practice.

All welding was done in a controlled environment, on a uniform substrate, by an experienced, skilled technician. The welding equipment was in excellent condition and fed by a clean, uninterrupted source of power. Even under these conditions some products allowed for little, if any, safety margin as defined in this study. Ideally, contractors should be working with products that provide the greatest level of safety over the broadest range of weld parameters and material conditions.

The results for TPO 2 and PVC E highlight the negative influence surface texture has on weld strength. It is not clear whether the lower results achieved with PVC E are the result of the thin sheet tested in this program, the physical properties imparted by the KEE component of the product formulation, a combination of both, or other factors.

As was observed in ancillary testing done in parallel with this program, focusing on weld width alone can be misleading. Ensuring the inner edge of a weld is continuous and straight is more important than the absolute width. Using the proper welding equipment, for example, a welder equipped with a spring-loaded air trap along the inside of the weld to compensate for surface irregularities, and a dedicated power source to minimize energy fluctuations go a long way to achieving the desired weld quality. Wider inconsistent welds will not compensate for the uneven loads imposed upon irregular inner weld edges which can result in pinholing under wind load.

The weld width topic merits further work to confirm or disprove the findings of the very limited testing done here.

Further study could also be envisaged to assess the effect of different atmospheric conditions (e.g., high and low temperatures) on the welding process for different thermoplastic materials.

A sufficiently comprehensive study of weld parameters, which would allow for a correlation between both laboratory and field measurements, might serve as the basis for the development of an ASTM standard. Such a standard, which should cover seam strength, surface preparation, and retention of seam strength as a percentage of original, would no doubt result in more consistent welding in all conditions in the field and ultimately, better performance. In the interim, contractors can increase their chances of successful installations by working with as few products as possible in order to build up their own experience and knowledge base of a product's welding behavior under all conditions.

Appendix: Standard Deviations

Welding Temp. T (°C)	Weld Speed m/min	TPO 1 lbf/in.	TPO 1 Std. Dev	TPO 2 lbf/in.	TPO 2 Std. Dev	PVC 1 lbf/in.	PVC 1 Std. Dev	PVC E lbf/in.	PVC E Std. Dev	PVC 2 Std. Dev
As Received										
350	1.5	64.1	7.04	38.1	1.61	12.2	6.18	28.2	7.65	66.4
350	2	64.8	14.43	38.9	2.41	4.4	2.38	31.4	1.89	75.1
350	2.5	65.9	6.15	39.5	1.43	3.7	3.91	28.5	4.65	69.3
400	1.5	65.5	2.99	39.4	1.08	68.5	2.81	32.6	3.84	64.5
400	2	68.7	1.90	39.8	0.21	18.3	13.78	31.5	4.85	62.0
400	2.5	69.9	3.33	39.8	1.14	12.4	3.32	34.5	2.01	68.4
450	1.5	61.8	2.63	40.0	1.59	69.9	6.95	38.6	7.35	58.1
450	2	67.1	4.36	40.5	2.23	71.9	4.94	34.9	5.24	63.5
450	2.5	68.8	5.73	39.6	1.76	69.4	16.72	25.1	8.34	65.4
500	1.5	64.6	9.90	40.0	3.69	69.6	5.44	38.2	4.70	65.5
500	2	69.4	5.36	40.3	1.58	77.0	5.53	41.2	3.79	53.1
500	2.5	67.0	3.85	39.9	1.52	69.3	10.10	32.1	2.23	56.1
After Immersion										
350	1.5	53.0	3.06	27.2	10.88	39.9	4.88	29.5	0.78	68.3

Welding Temp. T (°C)	Weld Speed m/min	TPO 1 lbf/in.	TPO 1 Std. Dev	TPO 2 lbf/in.	TPO 2 Std. Dev	PVC 1 lbf/in.	PVC 1 Std. Dev	PVC E lbf/in.	PVC E Std. Dev	PVC 2 Std. Dev
350	2	51.1	6.82	19.4	4.76	27.7	9.78	28.1	3.03	64.7
350	2.5	40.4	10.82	13.2	6.26	11.2	11.26	23.7	6.06	50.8
400	1.5	51.6	3.20	41.3	3.28	59.9	10.62	25.7	2.22	51.5
400	2	52.7	5.55	40.8	4.36	34.8	9.25	21.6	3.45	51.5
400	2.5	55.3	3.27	21.1	4.86	29.6	3.77	24.9	3.12	64.4
450	1.5	49.9	4.27	41.7	7.03	39.9	8.68	26.2	1.59	37.6
450	2	51.4	3.46	44.4	3.44	49.9	7.08	22.5	7.98	45.7
450	2.5	45.5	11.02	38.3	5.90	44.9	11.57	23.5	5.59	46.0
500	1.5	44.1	5.36	39.5	4.01	27.1	5.00	25.7	2.30	53.6
500	2	53.3	3.60	45.4	3.27	46.2	14.11	29.7	2.05	37.0
500	2.5	46.9	11.01	40.6	6.54	46.8	19.06	25.6	2.92	36.9
After Soiling										
350	1.5	52.1	6.39	38.0	4.83	60.0	5.40	23.0	2.52	6.17
350	2	55.3	4.25	34.3	1.90	55.8	7.73	28.6	1.13	65.9
350	2.5	42.4	3.87	23.7	4.97	40.9	21.51	26.2	1.39	63.7
400	1.5	52.1	2.69	33.6	3.00	44.5	7.24	23.3	2.81	70.9
400	2	54.3	6.24	32.9	4.46	37.5	5.64	24.9	3.28	69.1
400	2.5	44.4	6.95	31.6	8.89	43.1	10.35	24.8	4.26	72.2
450	1.5	46.2	5.08	38.6	3.29	55.8	6.18	27.7	1.00	64.1
450	2	48.4	5.42	31.8	7.19	52.1	4.94	21.8	2.70	66.2
450	2.5	43.0	4.79	25.8	4.12	49.1	11.04	23.8	3.23	70.8
500	1.5	37.0	9.35	35.2	2.87	58.5	15.66	30.3	4.70	67.5
500	2	51.6	3.82	37.6	2.60	75.4	7.02	24.3	2.16	69.3
500	2.5	52.8	5.26	36.0	1.40	77.0	4.50	26.7	1.85	74.7

References

[1] Simmons, T. R., Runyan, D., Liu, K. K. Y., Paroli, R. M., Delgado, A. H., and Irwin, J. D., "Effects of Welding Parameters on Seam Strength of Thermoplastic Polyolefin (TPO) Roofing Membranes," *Proceedings of the North American Conference on Roofing Technology*, 1999, pp. 56–65.