PHYSICAL TESTING of Thermoplastic Polyolefin Membranes and Seams

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INTRODUCTION

Single-ply membranes continue to gain roofing market share, with thermoplastic polyolefin (TPO) being increasingly accepted as a viable roofing option. Manufacturers typically do not significantly improve performance of their more mature products, instead engaging in cost reduction and manufacturing efficiency projects. In contrast, newer products often undergo improvement and further development to meet greater demands of the marketplace and gain market share. TPO has followed the latter route and has been upgraded significantly since its introduction around 15 years ago.

TPO has not suffered from systemic issues, but some problems have been experienced by individual manufacturers. Those issues have sometimes led specifiers and contractors to search for ways to specify membranes to screen out manufacturers with whom they had a previous negative experience. This study will show that with respect to these highly engineered materials, it may be a mistake to single out any one property as a way of selecting a manufacturer. As with many materials, the track record of the supplier and the experience with that particular membrane are keys to successful selection. In fact, as installations are reaching 15 years and older without issue, TPO is increasingly regarded as a mature technology with proven performance.

As with all single-ply systems, TPO membranes provide no redundancy. Their watertightness depends both on the mechanical performance of the materials and the welded seams, together with the weathering resistance of the polymer. This paper examines the various tests that are used by the industry to ensure that physical performance is satisfactory. The key focus of TPO development recently has been longevity, and a future paper will examine how TPO is stabilized against UV and thermal breakdown.

TPO has been defined by ASTM standard D6878, the *Standard Specification for Thermoplastic Polyolefin-Based Sheet Roofing*, which was developed by Subcommittee D08.18 on Nonbituminous Organic Roof Coverings. The real-world performance of any roofing membrane depends not only on the initial physical properties but also on the installation methods, total system design, and a myriad of other factors. D6878 sets a minimum threshold for the physical properties of a TPO membrane.

This work uses the tests set out in D6878, together with some other physical tests that are in widespread use by the industry, to show how commercially available TPO membranes perform. The tests are reviewed in some detail, and their relevance is discussed. Note that these membranes usually consist of two film layers of TPO sheet laminated together with a reinforcing polyester scrim in between. This is the type studied here, and other variations were not tested.

Procedure

Eighteen commercially available TPO rolls were obtained for this study. The manufacturing date codes covered the second half of 2008 and the first half of 2009. Six 45-mil, nine 60-mil, and three 80-mil samples were obtained, with all suppliers being represented by at least two samples. The performance of these membranes is compared with the ASTM minimums.

In any study of this type, the absolute values obtained should be treated with caution. There is a temptation to compare the data with what is shown in the manufacturers' product literature. However, that can be misleading for several reasons:

- The sampling here provides a "snapshot" and not any kind of average of a particular manufacturer's product properties.
- Published product data vary in terms of what they actually represent. In some cases, the ASTM D6878 minimum requirements are shown; in others, so-called typical values, and sometimes manufacturing targets are indicated.
- While every effort was made in this study to ensure accuracy and avoid bias, the data shown were not validated in any kind of round-robin study. Test frequency depended on the measurement, but generally each roll was studied at multiple points along and across the sheet. Measurements were made by a sin-

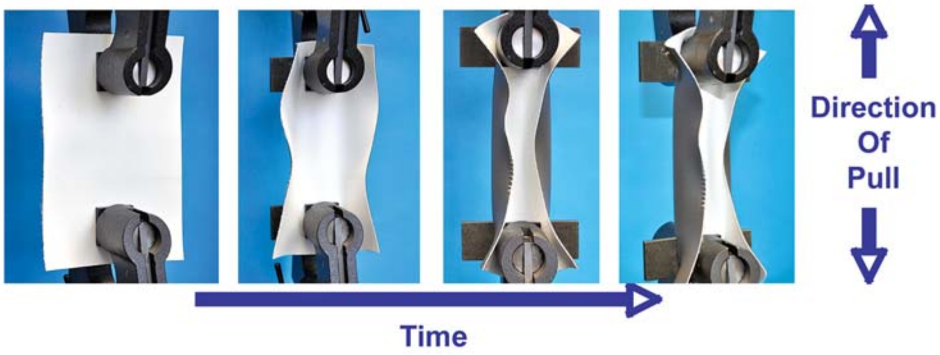


Figure 1 – Breaking strength measurement using ASTM D751. The left picture shows the membrane immediately after clamping, with no force applied. The far right picture shows the membrane just past the point of maximum force.

gle laboratory with experienced technicians, but testing such as thickness over scrim may be somewhat dependent on operator and technique.

Breaking Strength

Breaking strength is measured by pulling the membrane in opposite directions, using a grab-test method and recording the pounds of force needed to break the membrane. Importantly, the force recorded corresponds to the breakage of the scrim, after which the top and bottom polymer layers often remain intact to a point of considerable extension or stretch. Breaking strength is measured both across and down the sheet (cross and machine directions). See *Figure 1*.

ASTM D6878 requires a minimum of 220 lb of force in each direction. In practice, TPO is very easily stretched; therefore, many producers will state that the scrim provides the membrane strength. However, this is only partly true; and polymer strength, membrane thickness, and probably compositional parameters play a role. *Figure 2* shows average breaking strength (machine direction [MD] and cross-machine direction [CMD], in lbf) and the D6878 minimum requirement.

The MD/CMD average ratio was 1.08, with a standard deviation of 0.05, indicating that commercial membranes are generally isotropic, with a very slight bias toward machine direction strength. This is almost certainly due to the scrim design.

Note that all samples exceeded the ASTM D6878 minimum of 220 lbf by a wide margin. When viewing the data shown, it may be tempting to assume that for a given thickness, the higher breaking strengths are superior membranes. However, there are some key factors that may indicate otherwise:

- It is possible that higher strengths can be achieved by increasing the TPO content but decreasing the other components, such as fire retardants, stabilizers, and pig-

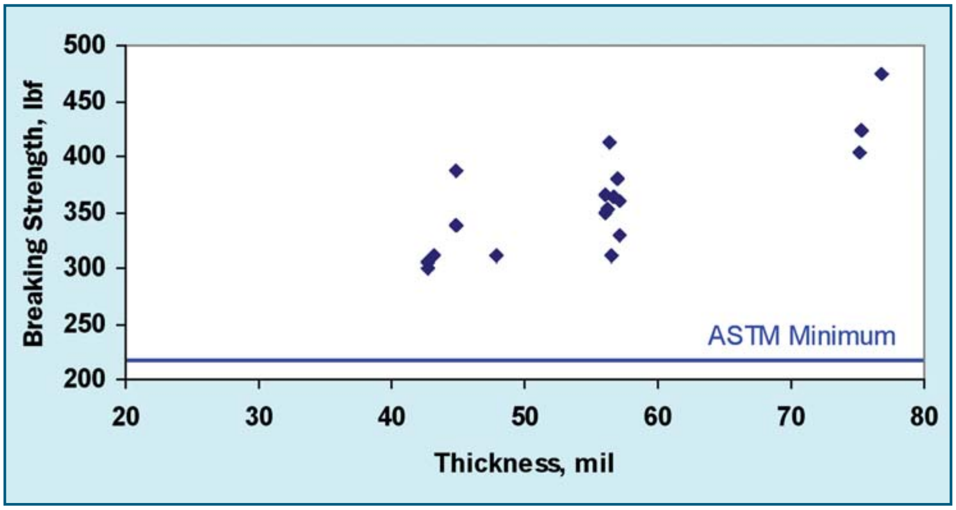


Figure 2 – Average breaking strength, MD and CMD, versus thickness for a range of commercial TPO samples produced in 2008 and 2009.

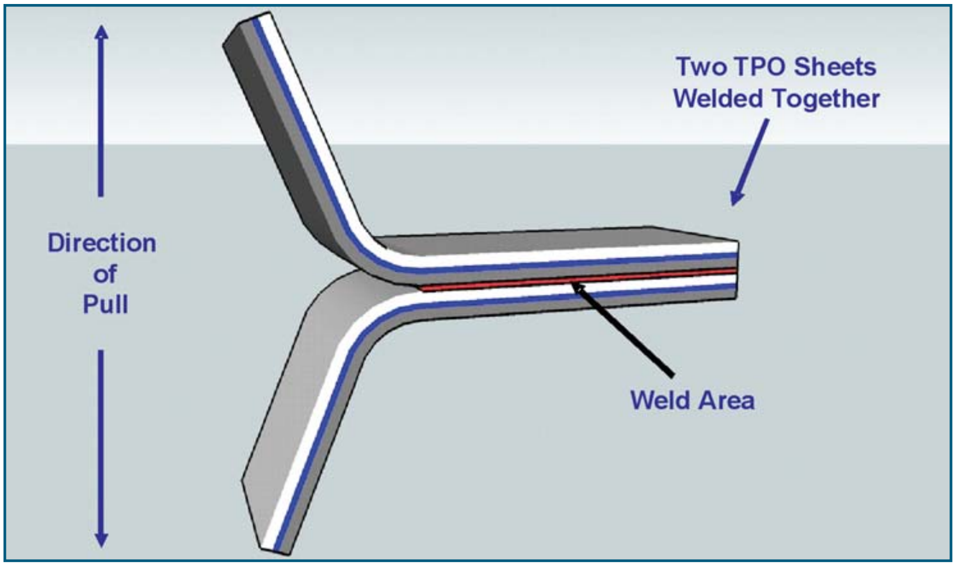


Figure 3 – TPO sheets welded together prior to T-peel testing for lamination strength.

ments. This would obviously degrade other important attributes. Similarly, a heavier denier scrim would raise strength, but due to a reduction in spacing between yarns, the lamination strength would be negatively affected.

- There are several types of TPO polymer available. The authors have seen some stronger polymers, but welding, flexibility, and weathering resistance may be compromised.

For these and other reasons, the temptation to set membrane requirements too far above the D6878 requirement should be resisted. The breaking strength provides resistance to breakage during wind uplift events; but total system design, including fastener design and patterns, ensures that needs are met. There is no clear evidence that the breaking strength of commercial TPO is insufficient for end use requirements.

Ply Adhesion

As indicated earlier, TPO membranes consist of two polymer layers laminated together with a reinforcing scrim in between. There is essentially no adhesion of the scrim to either layer, and all of the lamination strength results from the layers fusing together between the open windows in the scrim. The industry refers to the strength of this fusion as the ply adhesion.

Ply adhesion is not directly addressed in ASTM D6878, but all manufacturers follow some form of the procedure described in *Figure 3*. This is a T-peel test conducted according to ASTM D1876. To exert a pull to separate the two plies, two strips of membrane are welded together as shown. The strips are then pulled apart as indicated in *Figure 4*.

Providing that the weld was performed correctly, the failure point during this T-peel test will be between the two layers in one of the sheets. This is because in the weld area, there is 100% fusion between the two TPO membranes, whereas between the layers, the scrim occupies some of the area and prevents 100% TPO-to-TPO lamination. There is an initial maximum load caused by breakage at the edge of the weld area, fol-

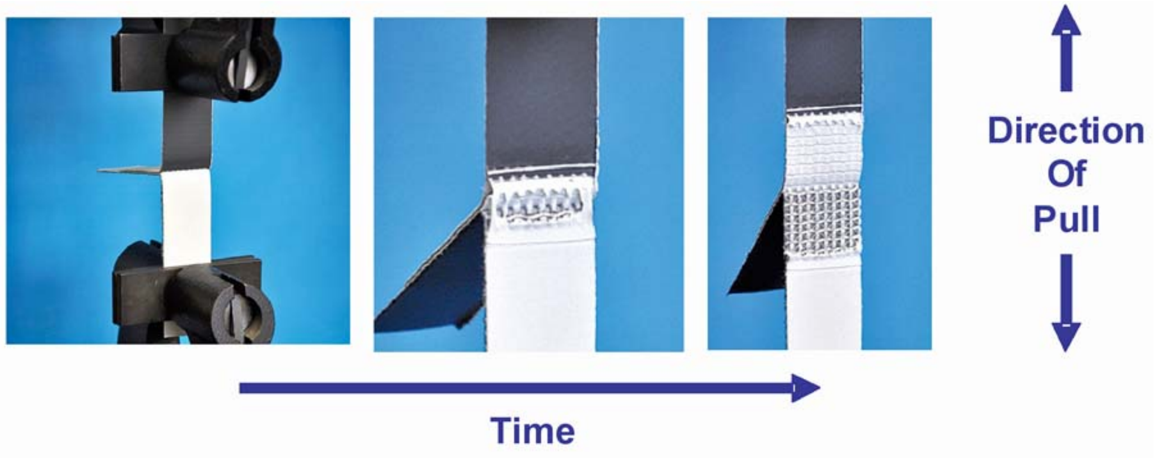


Figure 4 – T-peel test showing delamination between cap and core membrane plies, thereby indicating lamination strength.

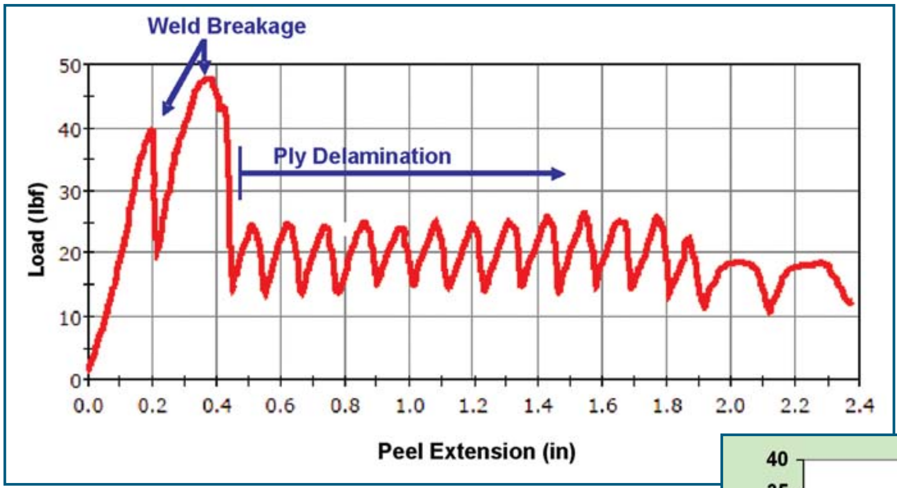


Figure 5 – Typical load versus peel extension result from a ply delamination test.

lowed by a series of lower peak loads during delamination of the membrane, as is shown in *Figure 5*.

The ply adhesion is calculated by the average load during the first five delamination events, shown as a function of membrane thickness in *Figure 6*.

As would be expected, lamination strength appears to be independent of membrane thickness. However, the range of values does appear to be very high. ASTM D6878 does not provide any guidance as to how low-ply adhesion can go without there being field failures. It is reasonable to expect that, since these membranes are composite structures, the weakest link will limit performance.

Although the lamination strength required to avoid field issues is not known with precision, the authors are not aware of widespread field failures associated with delamination. Anecdotal evidence suggests that when delamination failures do occur, the cause

Figure 6 – Ply adhesion, shown as the average load during five delamination events, versus membrane thickness.

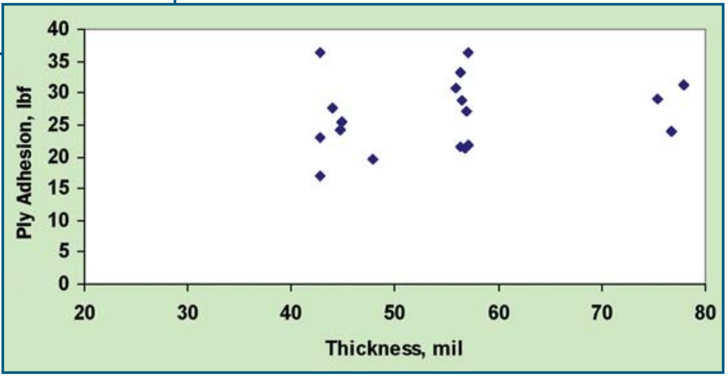


Figure 8 – Seam strength test showing the sample mounted, before full tension is applied and after break at maximum load.

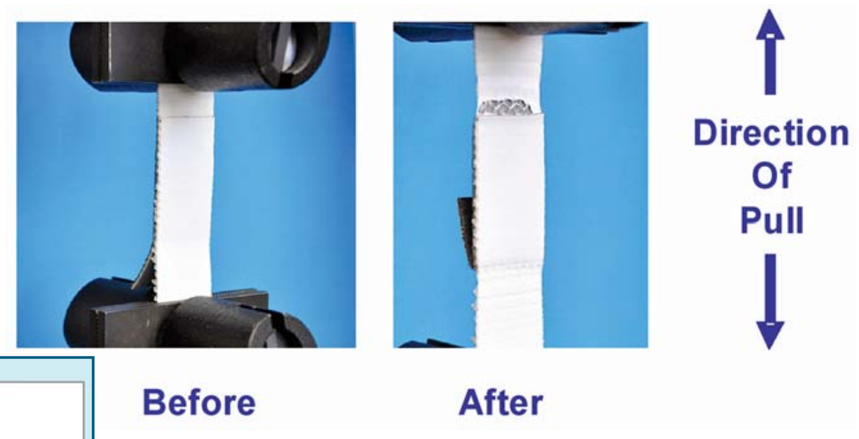
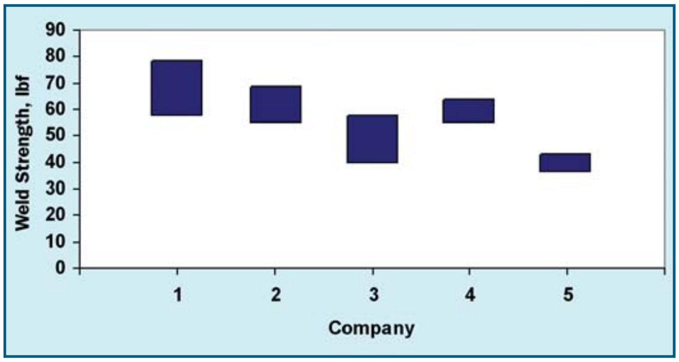


Figure 7 – T-peel weld strength as a function of the manufacturer.



can be attributed to manufacturing issues. In fact, it appears that lamination failure in the field can be initiated by poor lamination in a very small area that then propagates across the field. Experienced manufacturers know how to ensure that such weak spots do not occur. The best guides to lamination performance are a manufacturer's experience and a specifier's comfort with that manufacturer.

WELD STRENGTH

Welds are stressed in one of two ways: either in a shear mode or in an angled peel mode. These are reviewed separately.

T-Peel Test

Turning back to the typical delamination test result in *Figure 5*, it can be seen that the other data point of value from the T-peel test is the initial breakage load due to the weld's cohesive failure. This mode of failure best mimics what would be seen under a high wind-uplift scenario in mechanically attached systems. This load does not correlate with any other physical property; but, when viewed as a function of the manufacturer, there is a suggestion that some processes and/or formulations are achieving higher strengths, as shown in *Figure 7*.

Obviously, the limited number of samples tested for each individual manufacturer makes it difficult to draw any firm conclusions. It again suggests that as long as a specifier is having success with a manufacturer there should not be a cause for concern.

There has been some suggestion that TPO T-peel strengths can be as low as 26 lbf and that adhesive failure between welded surfaces is a frequent occurrence.[1,2] In practice, TPO membrane welds are tested during installation to ensure successful welding and a cohesion. In fact, the authors are not aware of any adhesive failures except when welds were done outside of recommended weld temperature and speed recommendations.

Seam Shear Strength

On a roof, welded seams are sometimes stressed in a shear mode. The test described in ASTM D6878 mimics that stress as shown in *Figure 8*.

As in the weld T-peel test, if the weld was carried out correctly, then the failure mode will not be the weld itself. Instead, the membrane tears alongside the weld as shown.

Close observation of the specimen at the immediate point of breakage shows that as the membrane breaks, one of the scrim CM yarns also breaks. The observed breaking strength is very poorly correlated with any other individual property. As would be expected, the best fit is obtained with the cross-machine breakage strength, but a straight-line model yielded only an $r^2 = 0.423$.

By modeling all of the physical property data, the best fit ($r^2 = 0.613$) was obtained using the following model:

Seam Strength = T-Peel Weld Breakage + 2(Thickness over Scrim)

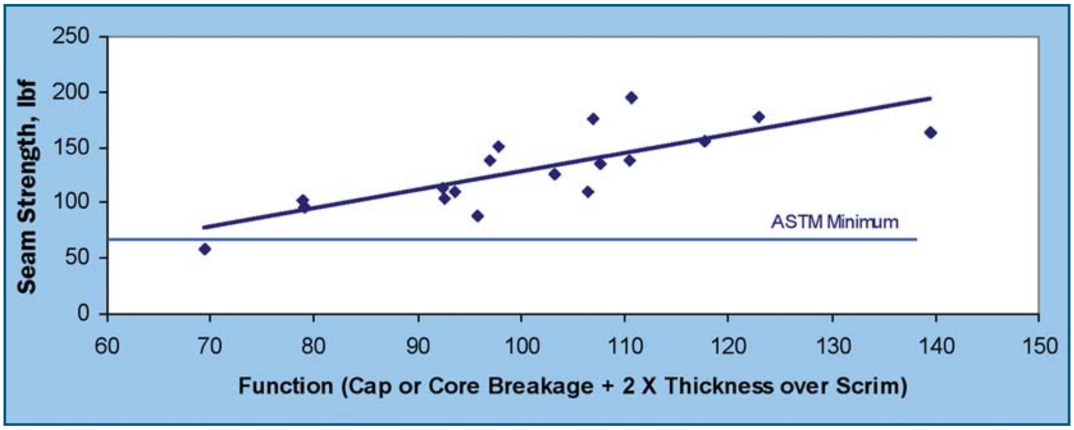


Figure 9 – Seam strength as a function of cap or core breakage and thickness over scrim.

This is shown in *Figure 9* and suggests that weld strength and thickness over scrim are important for breakage adjacent to welds.

The model is best understood by closely examining the forces involved during the seam adhesion test. As noted earlier, for a good weld, the failure always occurs immediately adjacent to the weld. At that point, the membrane does not experience forces that are entirely par-

Tear Strength	Average, lbf Deviation	Standard	Range, lbf
MD	108.4	35.6	53.0 – 185.9
CMD	142.9	19.2	102.7 – 171.2
Ratio (MD/CMD)	0.76	0.24	0.47 – 1.23
Total (MD + CMD)	251.2	45.0	155.7 – 299.6

Table 1 – Tear strength results for 18 commercial TPO membranes.

allel to the sheet, and some cross forces come into play. For that reason, cap strength and thickness over scrim play a role.

Interestingly, if one considers the ASTM D6878 minimums for thickness over scrim (12 mil) and assumes a weld T-peel strength just below that of the minimum measured here (35 lbf), then a seam strength of 59 lbf is predicted. Since few of the commercially available materials have seam strengths near this value, this may be an area where the standard TPO specification could be improved.

Tear Strength

Tear strength is most relevant to the behavior of membranes around a fastener during high wind events. A summary of the tear data is shown in *Table 1*.

Note that MD tear refers to a tear along the machine direction (some industries reference the torn reinforcement yarn direction). No correlation was found between the measured tear values and any other physical property, including thickness or lamination strength, suggesting that tear strength is primarily a function of the polymer and other additives. However, when viewed as a function of the manufacturer, this also appears not to be the case, as shown in *Figure 10*.

These data suggest that any study that uses only one roll of product from each manufacturer could give a misleading representation. The results indicate that either the test is subject to error and/or that there is another source of variation that was not identified. However, the ASTM D6878 minimum tear of 55 lbf was exceeded, sometimes by a wide margin, in almost every case.

Thickness Over Scrim

There is a widespread belief in the industry that membrane thickness over scrim is directly related to the ability of a membrane to provide long-term waterproof integrity. In this study, that distance from the top of the weathering layer to the highest points of the reinforcing scrim was measured to determine if there was a relationship to any other physical property. Such a relationship was found only for the weld strength data, as described earlier.

Figure 11 shows the thickness over scrim, TS, versus total membrane thickness, TM, for all 18 commercial samples measured. On average, the TS is 39.4% (s.d. 4.4) of the TM, the relatively small standard deviation indicating that the manufacturers are fairly consistent in their placement of the scrim.

There is a surprising degree of overlap between results for the three different total thicknesses, especially for the 45- and 60-mil products. Certainly, all exceed the ASTM D6878 minimum of 12 mil. As has already been stated here, specifiers need to be comfortable with a manufacturer's membrane since the data themselves do not indicate how well a membrane will perform in the field.

CONCLUSIONS

1. In this examination of the physical properties of 18 TPO membranes, representing all of the manufacturers with a commercially available product, the ASTM D6878 requirements were generally met and frequently exceeded by a wide margin.
2. Given the absence of systemic and industry-wide failures, this study

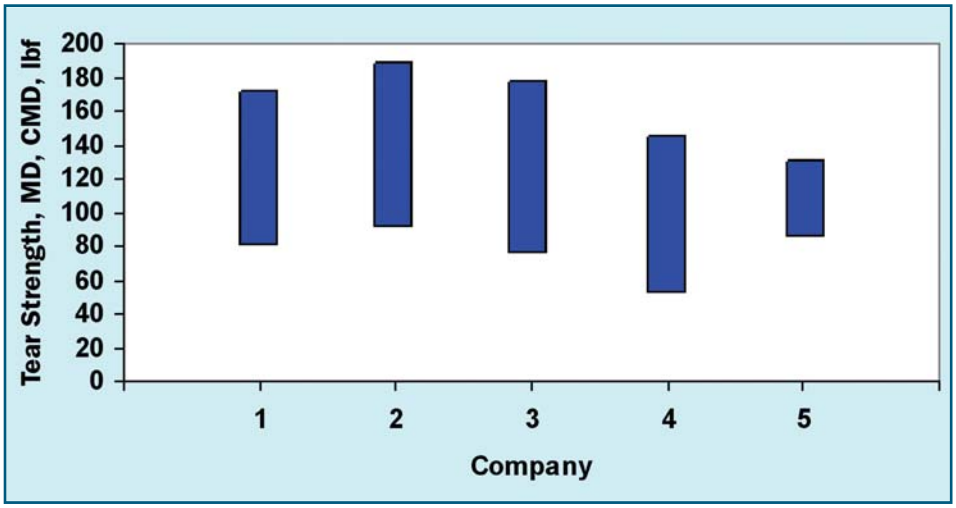


Figure 10 – Tear strength of commercial TPO membranes comparing manufacturers.

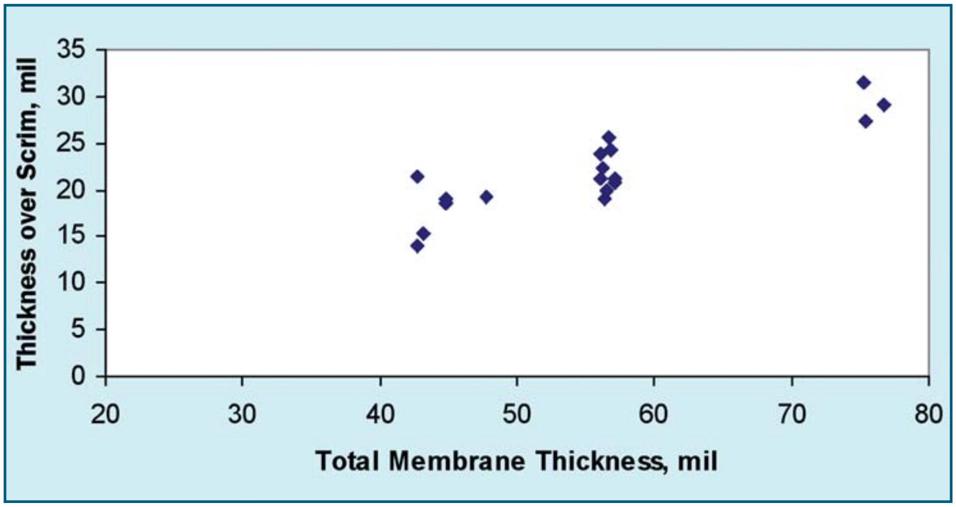


Figure 11 – Thickness over scrim as a function of total membrane thickness.

clearly suggests that, with respect to initial performance, the requirements do indeed ensure the minimum quality for the intended purpose. Restated, field failures during the initial years are most likely associated with application issues and/or manufacturing defects. Specifiers should rely on their experience with specific manufacturers and the historical record of that company.

3. There is no evidence that the requirements in D6878 are too low, so raising the minimum requirements is probably without merit, at least with respect to initial physical performance. In fact, to meet more rigorous requirements, it may be necessary to compromise with respect to other properties. For example, breaking strength could be improved by increasing the polymer content, but then fire and weathering performance could be reduced.
4. TPO is a highly engineered membrane, produced on relatively sophisticated equipment. The overall balance of properties that each manufacturer achieves is the result of careful optimization of polymer chemistry, the various additives needed for fire and weathering performance, and process variables. To focus on one or two properties as a means to specify a membrane would be a mistake that could result in suboptimization of many other key properties.

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2. S.P. Graveline, “Welding of Thermoplastic Roofing Membranes Subjected to Different Conditioning Procedures,” *Interface*, pp. 5-10, March 2009.

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