Testing Field-Aged TPO Roofs; Demonstrating Real-World Performance

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INTRODUCTION

Single-ply membranes are currently the biggest segment of the commercial roofing market. Within that segment, thermoplastic polyolefin (TPO) is both the largest and the fastest-growing sub-category. The first TPO roof in North America was installed as a demonstration project in 1986,[1] and the membrane was commercialized around 1990.[2] Since then, the installed area of TPO is estimated to be in excess of 20 billion square feet.

The longevity of any material routinely exposed to the rigors of weather, sunlight, and even pollution is difficult to predict from laboratory studies. This is true for materials such as paints, siding, paving, and, of course, roofing. Accelerated aging techniques can provide useful data indicative of long-term performance, but they don't take into account the combinations of challenges seen by materials in real-world scenarios. TPO membrane has now been installed on roofs for several decades, making a meaningful and representative field survey of its performance possible. The goal of this study was to evaluate TPO samples taken from older installations in terms of their properties as compared to their original specification. The installations were intended to cover a wide geographic range, in order to evaluate TPO's performance in as variable a range of climatic conditions as possible. In addition, having taken samples from aged roofs, it was possible to evaluate their repairability, should such a need arise.

BACKGROUND

TPO Formulation

Early formulations contained brominated fire retardants, which caused unanticipated weathering and premature degradation issues.[3] By 1994, manufacturers were using magnesium hydroxide as the fire retardant, and this remains the case today. Also in the early 1990s there were some significant variations in the polyolefin being used. But, by the mid-1990s, these had narrowed to the same basic type that is in use today—i.e., propylene-rich ethylene-propylene elastomer.

Since the mid-1990s, TPO membranes have evolved with respect to the ultraviolet (UV) light and heat stabilizers being used to protect the polymer. This has come about both through improvements in stabilizer technology and a desire to extend service lifetimes. In addition, at least one manufacturer used more advanced stabilizers to increase membrane life when exposed to significantly higher-than-normal in-service temperatures.[4] The focus on heat exposure came about because it appeared from in-service performance that heat and not UV was responsible for a large number of premature failures being experienced by some manufacturers.

During a 2009 ASTM TPO task group meeting,[5] premature failure of TPO roofs was discussed. One manufacturer described membrane failures that were found to be related to unanticipated high heat loadings. In these conditions, the membrane was exposed to higher than normal temperatures due to situations such as reflections from nearby wall surfaces, HVAC units, and neighboring taller buildings.

In early 2010, the Midwest Roofing Contractors Association's (MRCA's) Technical and Research Committee published an advisory on TPO.[6] They noted, "Information is being circulated in the industry indicating that high solar loading and elevated temperature lead to the premature exhaustion of anti-aging components such as antioxidants, UV absorbers, and heat and light stabilizing compounds within TPO. This could lead to the breakdown of the sheet in affected areas."

Taylor has noted that there can be several causes of excessive heat buildup on TPO roofs.[7,8] These include nearby highly reflective surfaces, dirt, and directly adhered flexible solar panels. Subsequent testing of a large sampling of new membrane showed that there were large disparities in the accelerated aging performance of different manufacturers' TPO membranes.[9,10] However, that testing showed TPO accelerated aging performance to have significantly improved versus the initial formulations of TPO.

TPO Field Testing

A limited number of field studies have previously been conducted to evaluate the long-term performance of TPO roof membranes. A European study examined three TPO roofs that had up to 12 years in service.[11] All roofs were found to be performing well with no issues or change in membrane thickness. The peel and shear strength values of the sampled seams were similar to or higher than nominal values required by Standards UNI EN 12316-2, EN 12310 -1, and EN 12310-2. The researchers noted that "sampling actions on the roofs showed the perfect weldability and, therefore, the full possibility to repair membranes, even after years of operating exposure, by working on the inner side of the existing membrane." This indicates the repairs were successfully conducted by welding new membrane to the "inner side," also known as the core or the bottom side, of the aged membrane.

The Western States Roofing Contractors Association (WSRCA) conducted a 10-year study, beginning in 2000, with a final report being published in 2011.[12] It evaluated 60-mil white mechanically attached TPO membrane from four manufacturers in four different climatic regions in western North America.

The WSRCA researchers noted that "all of the TPO membranes examined in the field to date have proven to maintain their seam quality. All hot-air welded seams…are proving to have generally good weld integrity." One membrane had some cracking that was associated with a sharp crease that had been created during the original installation. That same membrane also exhibited some micro-cracking and crazing in a limited section of the Las Vegas test roof. It was concluded that this resulted from UV and heat exposure, in combination with a potentially less-robust TPO formulation. The survey noted that "some formulations obviously withstand heat-loading better than others."

WSRCA noted that additional preparation was needed for the repair of test cuts in some locations during the tenth year of exposure as compared to previous years. Specifically, a "solvent-scrub" step was added utilizing solvent and a scouring pad "to more aggressively remove a layer of oxidation on the surface."

In 2011, Beer et al. published a long-term field study on FPO (European terminology for TPO) membranes in service for up to 20 years in Europe.[13] The study predicted the in-service membranes would "fulfil their waterproofing function for further decades…provided they are used in compliance with the application and maintenance requirements," stating that the conclusion is "restricted to conditions within the moderate Central European climate and does not hold for dramatic climatic changes."

TPO Specification

The ASTM Standard D6878, *Specification for Thermoplastic Polyolefin Based Sheet Roofing*, was first published in 2003.[14] Note that this was approximately 13 years after the membrane was first introduced. The UV resistance was doubled in 2006, the heat aging requirement significantly increased in 2011, and the thickness-over-scrim definition was tightened in 2011. An option to heat-age at 275°F was added in 2017. In 2019, the standard was yet again updated to specifically identify the sampling procedures for heat aging.

Roof Sampling Program

The intent of this study was to evaluate field-aged TPO roof membrane performance and the ability to repair membranes as they age. Membrane samples were collected from roofs around the United States that were at least 12 years in service; the oldest sample was installed 18 years before this study began. Most of the roofs evaluated were installed between 2005 and 2006. All samples were from the same manufacturer and were predominantly 45- and 60-mil-thick smooth-back membranes. Samples were taken from mechanically attached, induction-welded, and adhered roofs. Self-adhered membranes were excluded from this study.

Samples were taken from 20 different roofs across the United States, as indicated in *Figure 1*. The buildings included offices, manufacturing facilities, retail outlets, libraries, automotive repair shops, warehouses, and a grocery store.

The roof projects' locations, membrane thickness, attachment type, and age are summarized in *Table 1*. Attachment type is described as adhered (A), induction-welded (IW), or mechanically attached (MA).

Figure 1 – Approximate locations of the 20 roofs sampled.

Location Code	Project Type and Location	Membrane Thickness (mil)			Attachment Type			Age, years	Date Installed
		45	50	60	A	IW	MA		
1	Office, Wayne, NJ		X		X			8.7	5/2011
2	Office, Wayne, NJ		X		X			8.7	5/2011
3	Office, Wayne, NJ			X			X	8.7	5/2011
4	Library, Bergenfield, NJ			X	X			14.5	8/2005
5	Mixed use, Atlanta, GA	X			X			14.0	2/2006
6	Retail, Berea, KY			X			X	14.7	5/2005
7	Office, King of Prussia, PA			X		X		13.2	11/2006
8	Retail, Lake St. Louis, MO	X					X	13.7	5/2006
9	Light industrial, Toms River, NJ			X	X			14.3	11/2005
10	Light industrial, Pennsauken, NJ			X			X	14.9	3/2005
11	Industrial, Mt Vernon, IN			X			X	18	2001
12	Retail, Oak Lawn, IL	X					X	13.2	11/2006
13	Aviation, N Charleston, SC	X					X	14.9	3/2005
14	MN	X					X	12	2007
15	Office, Dallas, TX	X					X	12	2007
16	Retail, Lake Mary, FL	X					X	16	2003
17	Industrial, Mt Vernon, IN			X			X	18	2001
18	Medical, Boise, ID			X			X	13	2006
19	Industrial, Gainesville, TX			X			X	12	2007
20	Restaurant, Mt. Dora, FL			X			X	17	2002

Table 1 – Locations #1–3 were part of the initial process to coordinate efforts with teams across the country for consistency. These roofs are a few years shy of the requirements set forth within this study.

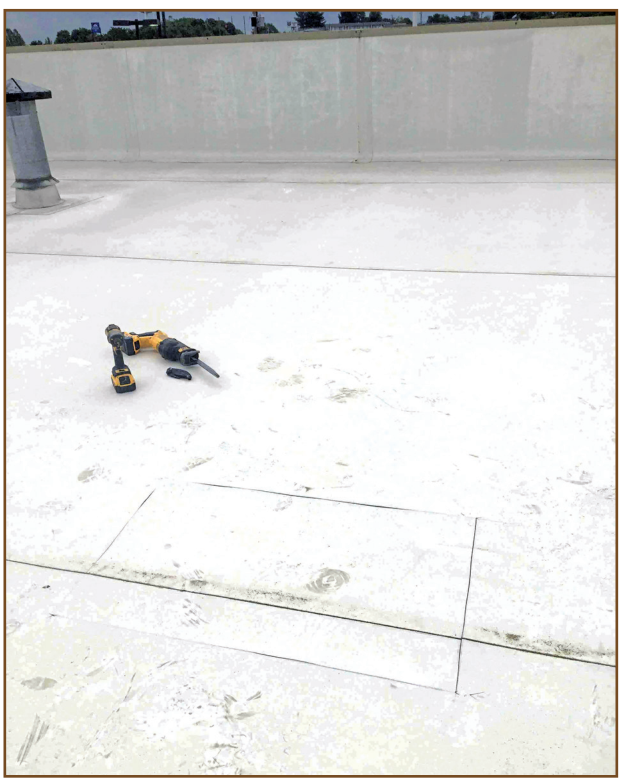

Figure 2 – Typical field sample (2 x 3 ft.).

SAMPLE SELECTION

Two samples were taken from each roof whenever possible. Each sample was approximately 2 x 3 ft. and captured a field-welded seam. One sample was taken from the field of the roof (*Figure 2*) and another was taken in a location that resulted in increased heat exposure by being near a south-facing parapet wall (*Figure 3*).

The large samples were cut into smaller pieces to evaluate membrane thickness, thickness over scrim, brittleness point, heat aging and weather resistance, ply adhesion of existing welds, and ply adhesion of repair welds. Each test was conducted on five unique specimens from each sample, and the results averaged.

TEST PROGRAM

The testing program evaluated those membrane properties that would be indicative of the roof's ability to maintain watertightness. Whenever appropriate, comparisons were made to the ASTM D6878 TPO material specification. It is important to note that the 2019 version of the specification is more stringent than the version in place when the membrane materials were manufactured. Instances where this could impact the conclusions have been noted in the results section. In every case, the ASTM D6878 specification being referred to here is the latest version that was promulgated in 2019.

In addition to watertightness, cool roof membranes such as TPO are used due to their ability to reflect the sun's energy and thereby lower air conditioning loads and mitigate urban heat island effects. Therefore, the solar reflectance (SR) of the samples was also evaluated.

Figure 3 – Typical sample cut near a parapet.

Membrane Thickness and Thickness of Coating Over Scrim

TPO membranes consist of two polymer layers of TPO—the cap (topside) and the core (bottom side)— which are laminated together with a polyester reinforcing scrim in between. Following ASTM D751 and D7635/D7635M, *Standard Test Methods for Coated Fabrics* and *Standard Test Method for Measurement of Thickness of Coatings Over Fabric Reinforcement*, respectively, the overall membrane thickness and the thickness of the coating over the scrim were measured.

Heat Aging and Weather Resistance

ASTM D6878 evaluates heat aging and weather resistance using ASTM D573, *Standard Test Method for Rubber—Deterioration in an Air Oven*, and ASTM G151/G155, *Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials*, respective test methods, which include a visual inspection of the membrane surface at 7X magnification when bent over a 3-in. mandrel for surface cracking. For the purposes of this survey, because the samples were field-aged, the ASTM D6878 visual inspection pass/fail criterion was used without applying the heat aging requirements.

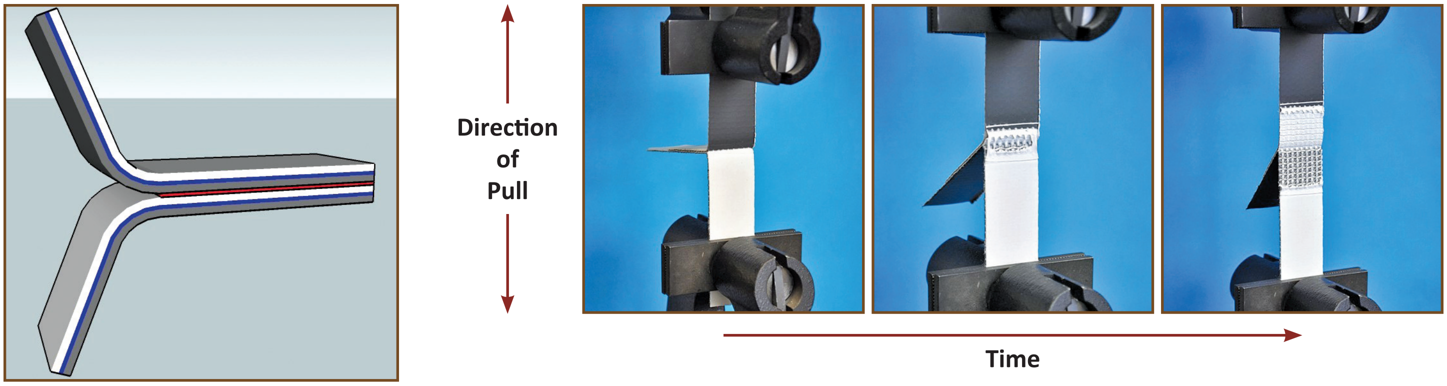

Figure 4 – Illustration of the ply adhesion test and a full film-tearing bond, indicating a complete weld.

Brittleness Point

Brittleness point, sometimes referred to as low-temperature flexibility, was evaluated per ASTM D2137, *Standard Test Methods for Rubber Property—Brittleness Point of Flexible Polymers and Coated Fabrics*, method B. Specimens taken from mechanically attached membranes were examined at 5X magnification for any visible fracture or crack in the cap layer after having bent the specimens to an angle of 180° in the same direction caused by the test impact.

Low-temperature flexibility testing was not conducted on adhered membranes, as remnants of the coverboard or insulation facer were adhered to the membrane core. This rendered the specimens too stiff to adequately test.

Aged Ply Adhesion

ASTM D1876, also referred to as the T-Peel Test, was used to evaluate weld integrity and membrane ply adhesion, as shown in *Figure 4*. The initial peak load caused by breakage at the edge of the weld area, and the series of lower peak loads during delamination of the membrane were recorded. The ply adhesion values reported are the average of the maximum load values at the initial break.

Ply adhesion testing of a proper seam weld will fail cohesively within one of the plies, exposing the underlying scrim. This is referred to as a "film-tearing bond" and indicates the integrity of the weld. For the purposes of this evaluation, anything over 70 percent film-tearing bond was considered a proper weld. *Figure 4* shows a 100 percent film-tearing bond at the end of the test, indicating a complete weld.

It is important to note that aged weld strength can be impacted by both the long-term weather exposure and the initial weld quality.

Aged Membrane Repairability

New TPO membrane was welded to the aged membrane roof samples to evaluate the ability to repair older roofs. Repairs with new membrane welded down onto the cap of the aged membrane—also called a

Figure 5 – Repair of aged TPO membrane with a new patch welded to the aged cap. Image courtesy of WSRCA.

Figure 6 – Repair of aged TPO membrane with a new patch welded to the aged core. Image courtesy of WSRCA.

top-down repair—were evaluated, with *Figure 5* indicating the general process. While this repair process is the most common, in some instances it is necessary to weld repair membrane to the core (the underside) of the aged roof, also called a bottom-up repair, as indicated in *Figure 6*. Both approaches were evaluated in this study. Note that weld strength to the core was not evaluated for cases of adhered membrane roof samples due to remnants of adhesive and/or facer from the insulation or cover board. Given the remnants attached to the underside of adhered membranes, repairs to the core would not be reliable.

In both cases, industry-standard cleaning protocols were followed for preparation of the test specimens used to measure weld strength and film-tearing bond. For consistency and to eliminate variables, a robotic welder was used at 12.1 ft./min. at 1148°F.

Aged Membrane Solar Reflectance

The solar reflectance of the aged membrane samples was measured according to ASTM C1549. While the test method allows for sample rinsing, that was not carried out in this study. Thus, this study is indicative of actual solar reflectance that is experienced by the roofs. Therefore, long-term adherence to energy efficiency and/or HVAC equipment sizing assumptions by the building designer can be checked.

RESULTS

Membrane Thickness and Thickness of Coating over Scrim

The membrane thickness-over-scrim (TOS) data for the field samples are shown in *Figure 7*.

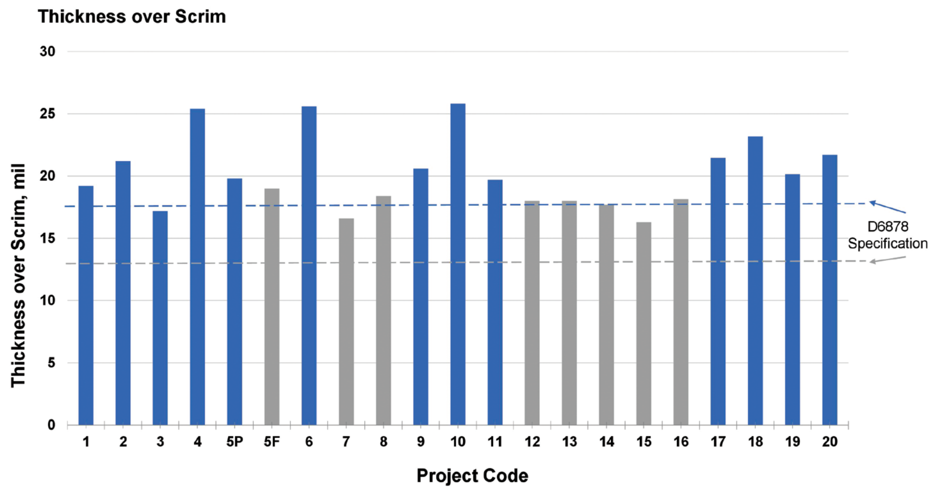

Figure 7. Membrane TOS 60-mil samples in blue, 45-mil in gray, with their respective ASTM D6878 minimum specification. Note that for Project 5, 60-mil membrane was installed at the perimeter and 45-mil membrane was installed in the field.

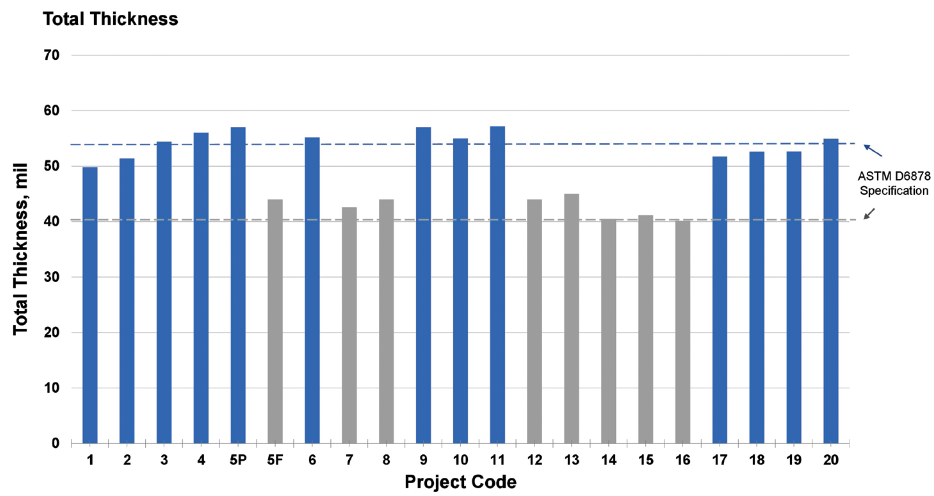

Figure 8 – Membrane thickness, nominal 45-mil in gray, nominal 60-mil in blue. Samples taken within the field of the roof. Note Projects 1 and 2 used a 50-mil membrane and comply with the ASTM thickness requirements.

TOS is a critical characteristic of single-ply membranes, because it is a measurement of the quantity of the weathering layer. Erosion of the membrane down to the reinforcing scrim layer may indicate failure and require repair or replacement. With one exception, all of the membranes tested show TOS values above the ASTM D6878-19 specification. For 60-mil membrane, this is 18 mil, and for 45-mil membrane, it is 13.5 mil. The results suggest that from the perspective of erosion, all of the membranes have significant remaining life.

As indicated in *Figure 7*, Sample 3 is 1 mil below the current ASTM minimum for TOS. However, this sample would have complied with the published ASTM requirements at the time of manufacture.

Total sample thicknesses for the field samples are shown in *Figure 8*.

As can be seen, some of the samples are below the overall ASTM D6878 minimum thickness. Total membrane thickness in Project 17 (an 18-year field-aged membrane) is 2 mils shy of the requirement for new ASTM membranes, while Projects 18-19 are 1 mil shy of the requirement.

It is somewhat in conflict with the TOS values, which are generally at or above the minimum. The apparent discrepancy between the two measurements suggests that the products included in this study were manufactured with a significant weathering layer, and after many years in service have maintained the critical TOS.

Samples taken from the perimeter might be expected to exhibit increased erosion of the weathering layer and, therefore, have reduced TOS versus the field samples. However, as indicated in *Figure 9*, this was not observed.

As seen in *Figure 9*—at least for the roofs where permission to obtain field and perimeter samples was granted—no consistent trends in terms of weathering were identified. This is an indication that the data are within the error tolerances of the measurement technique.

Heat Aging and Weather Resistance

Surface cracking was evaluated by visual inspection of the field-aged roof membranes at the time the samples were collected, and via inspection at 7X magnification when bent over a 3-in.-diameter mandrel. This evaluation is an important indicator of long-term performance.[10] Surface cracking

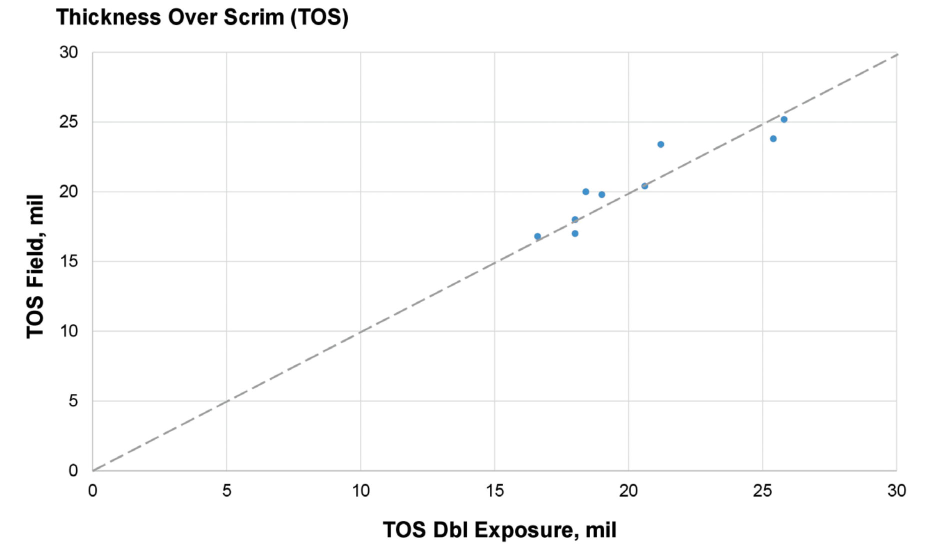

Figure 9 – TOS for the field versus perimeter samples. The diagonal line would be the result if no differences in weathering were observed. Samples in the field and perimeter were permitted on nine of the roofs in this study.

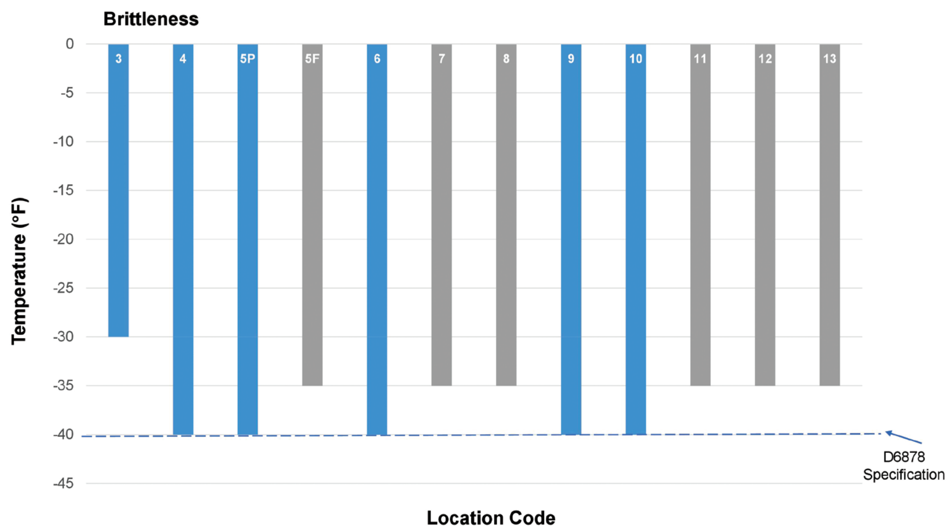

Figure 10 – Brittleness point of tested samples – nominal 45 mil in gray, nominal 60 mil in blue. Not all samples were tested for brittleness.

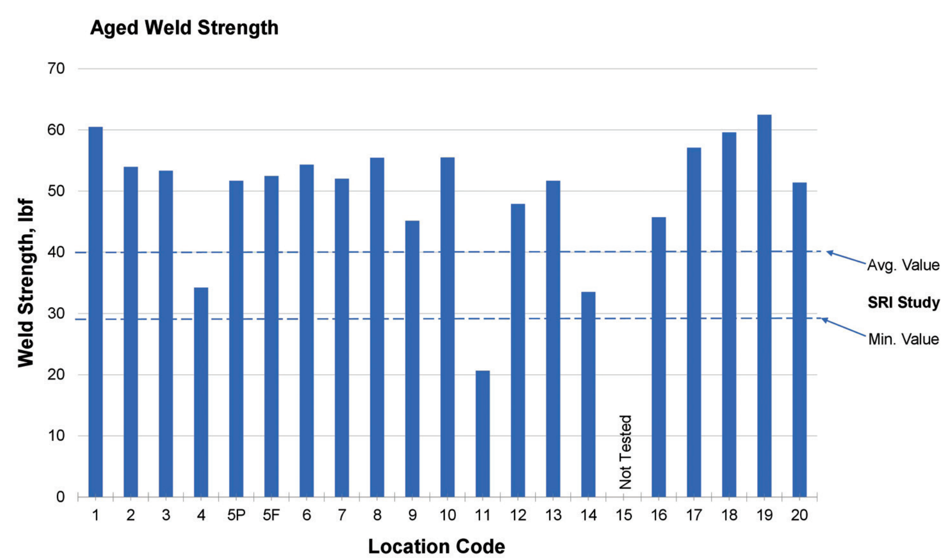

Figure 11 – Weld strengths of the aged roof samples.

on a roof is not indicative of an immediate problem until such cracks propagate down to the reinforcing scrim. Surface cracks are suggestive of the stabilizer content being substantially depleted, which could lead to more rapid deterioration of the membrane. None of the samples—neither the 45- nor 60-mil membranes—exhibited any signs of surface cracking when bent over the mandrel and viewed at 7X magnification.

Brittleness Point

The aged roof samples were evaluated for brittleness point, an indicator as to whether the membranes become more susceptible to cracking during extreme cold conditions. Only those samples that had been mechanically attached were tested, with the results being shown in *Figure 10*.

ASTM standard D6878 requires new membranes to have a brittleness point of -40°F or lower. All except one of the 60-mil samples tested still meet cold temperature flexibility requirements after field aging. The 45-mil samples showed initial signs of cracking at -35°F. The slight rise seen for these samples is indicative of low-temperature stiffening due to oxidative crosslinking. Roofing membrane issues caused by rising brittleness point were previously observed with early versions of PVC, which exhibited cracking and shattering during winters.[15] However, such issues were essentially eliminated by improving the formulations and by the use of reinforcing scrim. The scrim used in TPO is the same basic design and type as used in PVC, and the small changes in brittleness point observed in some of the sampled TPO roofs are not a cause for concern. However, the data support the use of thicker membranes for longer-term performance.

Aged Ply Adhesion

The weld strengths of the roof samples are shown in *Figure 11*.

ASTM D6878 does not provide a minimum value for weld strength. Weld strength is compared to the values published in a study of new TPO membranes conducted by Structural Research, Inc. (SRI). This study included a broad TPO sampling of all industry manufacturers.[16] This previous study of the weld strength of all thicknesses of TPO from all manufacturers showed most new samples to exhibit weld strengths between 45 and 75 lbf.[17] Film-tearing bond, as shown in *Figure 12*, was also analyzed as it is relied upon in the field to assess the

Figure 12 – Film tearing bond of nearly 100 percent, from Location 6.

qualitative integrity of a weld.

All of the samples except Location 11 had comparable values to the SRI Study. For Location 11, the value of 20.7 lbf is indicative of a suspect-quality weld and would require further investigation. This is also suggested by the film-tearing bond data, summarized in *Figure 13*.

All of the samples except Locations 4 and 11 met the threshold requirements for percent film-tearing bond. Comparing the weld strengths and film-tearing bond percent, it is clear that the roofs at Locations 4 and 11 might warrant further investigation due to the combination of low weld strength and film-tearing bond. In the case of Location 2, the aged membrane has a weld strength of 53.9 lbf with a film-tearing bond less than 70 percent. This suggests that the issue on this roof could be local-

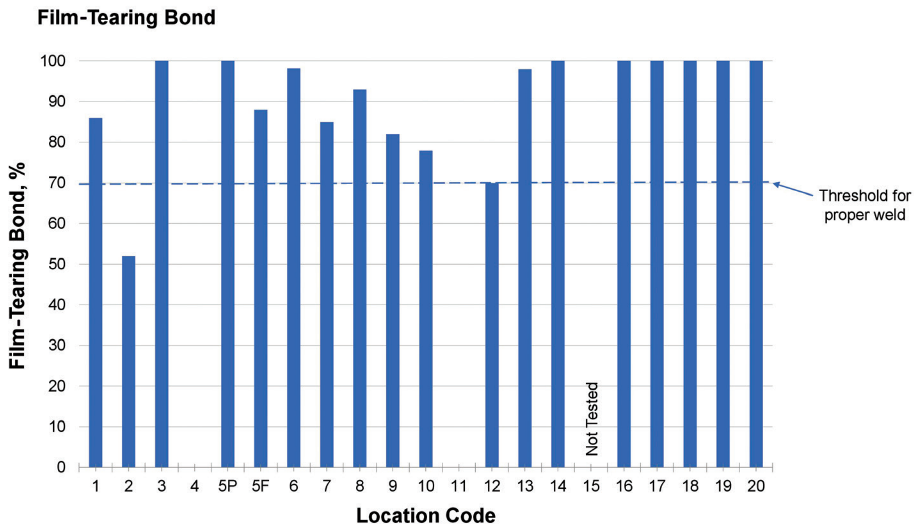

Figure 13 – Percent film-tearing bond of the aged roof samples. Zero film-tearing bond at Locations 4 and 11 suggest poor-quality workmanship.

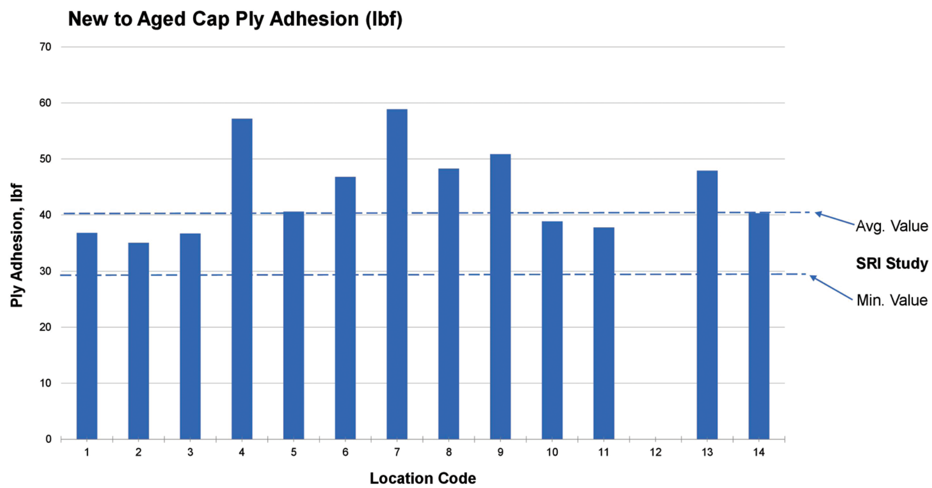

Figure 14 – Ply adhesion of the new membrane to the aged cap. The average ply adhesion was 44.7 lbf/in. Not all samples were tested for ply adhesion.

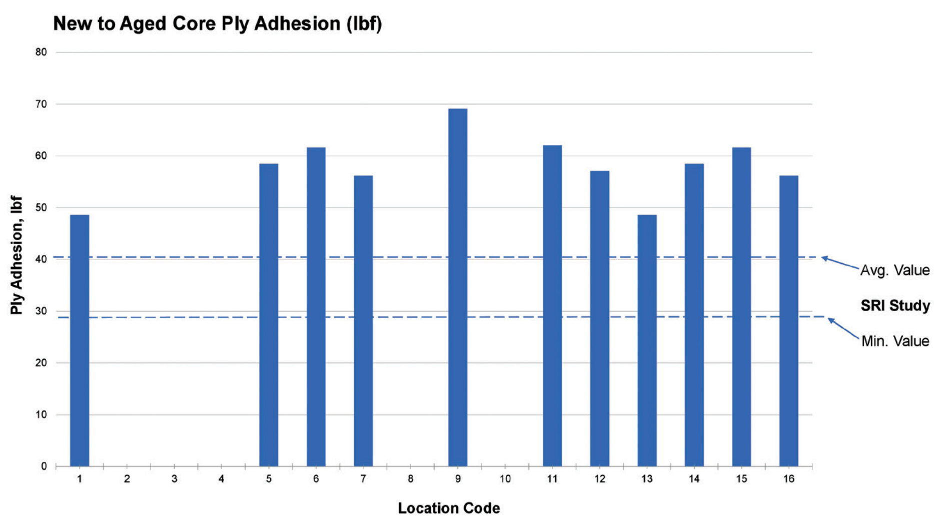

Figure 15 – Ply adhesion of the new membrane to the aged core. The average ply adhesion was 58.8 lbf/in. Adhered membranes were excluded from this evaluation.

ized, possibly to the installation time of day and ambient conditions.

Normally, welder settings are evaluated and adjusted throughout the day during installation to compensate for ambient temperature changes, and the film-tearing bond is visually evaluated to confirm the membrane is properly welded together. If the sample fails and the scrim is not exposed, or the film-tearing bond is not greater than 70 percent, the contractor adjusts the heat and/or speed at which the welding equipment is being used.

For frame of reference, new TPO membrane samples included in a broad TPO sampling study of all industry manufacturers conducted by SRI averaged a ply adhesion (T-peel) value of 40 lbf/in., with a minimum value of 29.3 lbf/in. Previously, however, Simmons et al.[18] found that the ply adhesion tests typically failed adhesively, meaning there was not a strong bond between the welded TPO layers, and the film-tearing bond was 0 percent when the ply adhesion of the seam weld was 26 lbf/in. or less.

The ply adhesion values of the aged TPO membrane seam welds were, on average, 15 percent above the average ply adhesion value from the SRI study on new TPO membranes. Therefore, as expected, the aged welds appear to be performing well and are of adequate strength.

Aged Membrane Repairability

The ply adhesion of the new membrane to the aged cap averaged 44.7 lbf/in. (standard deviation 8.9 lbf), as shown in *Figure 14*. For the new membrane welded to the aged core, the ply adhesion averaged 58.8 lbf (standard deviation 7.5 lbf), as shown in *Figure 15*. Both values represent the combined 45- and 60-mil thicknesses.

The ply adhesion values of new repair membrane to the core of the aged TPO membrane are above the average ply adhesion value of 40 lbf/in. from a large independent study of new 60-mil TPO membranes conducted by SRI.[16] This provides validity to the integrity of repairs to aged TPO membranes and the ongoing maintainability of these roofs. It should be noted that ultimate ply adhesion is mainly a concern for wind uplift of mechanically fastened systems as shown in *Figure 16*.

Typically, repairs of single-ply membranes are made to punctures within the field of the membrane. As such, they usually represent a very small fraction of the membrane area and, essentially, the overall mechanical strength is not significantly impacted. The reinforcing scrim can redistribute loads around a small repair. For systems where the membrane is adhered to the substrate, ultimate membrane and ply adhesion are also not as critical.

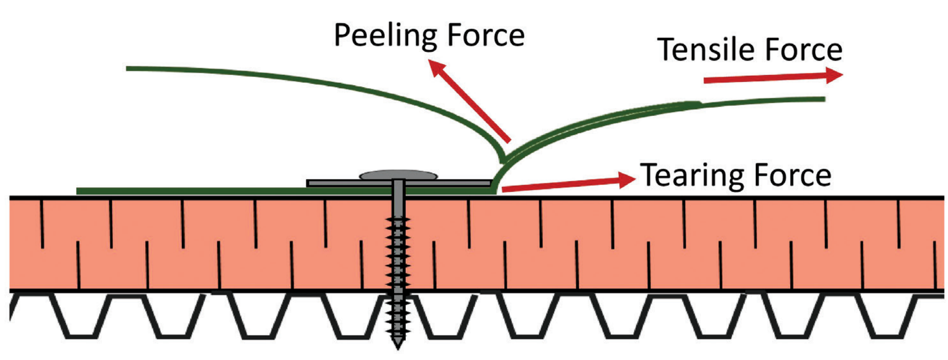

Figure 16 – Schematic showing the three main forces applied to a mechanically attached membrane during a high wind event.

Aged Solar Reflectance

The aged solar reflectance values are shown in *Figure 17*. With the exception of Locations 17 and 18, the roofs showed an average value of 0.665. This is only slightly below the three-year aged solar reflectance of 0.68 reported by the Cool Roof Rating Council (CRRC) for this membrane.[19]

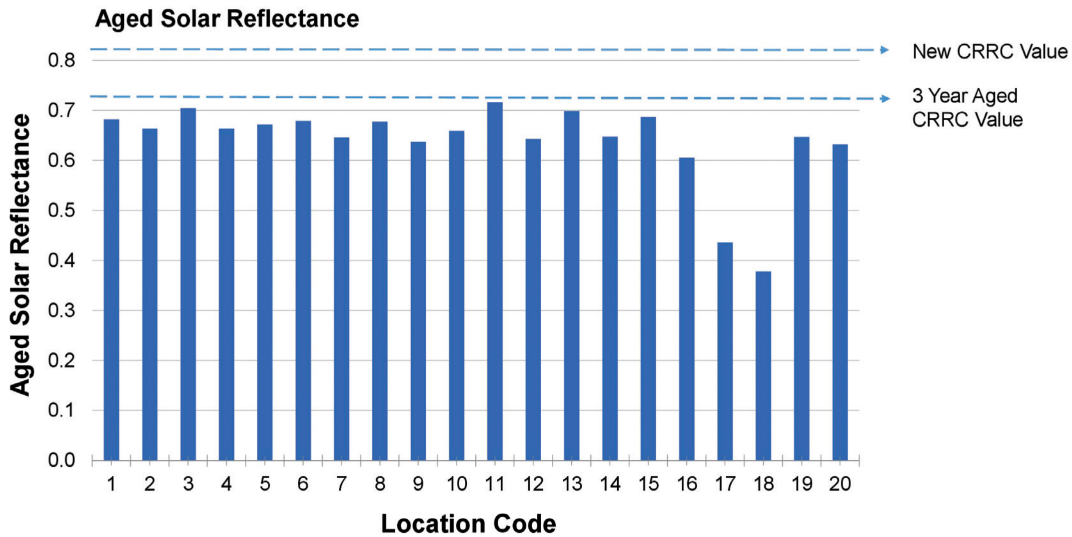

Figure 17 – Solar reflectance values of the aged cool roof membranes.

The 0.44 and 0.38 values exhibited by Locations 17 and 18, respectively, suggest that the area sampled was particularly contaminated—a condition that could possibly be resolved by cleaning. Many roofs have localized contaminated areas, such as those that occur near drains or low points. Taken overall, the results suggest that the published three-year solar reflectance values generally can be used to model long-term energy efficiency of these roof systems.

CONCLUSIONS

The data collected for the 20 aged TPO roofs evaluated suggest that the membranes are performing well. There were no geographical differences noted, and the results indicated that the roofs are capable of achieving their expected service lives.

The ply adhesion values of new repair membrane to the aged TPO membrane are primarily above the average ply adhesion values anticipated for new TPO membranes. This provides validity to the integrity of repairs to aged TPO membranes and the ongoing maintainability of these roofs.

In a few instances, the film-tearing bond was below expectations. The data suggest that there were issues with the workmanship in these few cases, which points to the importance of weld quality checks throughout a roof installation. These would involve test welds to determine the percent of film-tearing bond.

The TOS values for all roofs tested suggest that there is little to no erosion of these membranes. Also, no instances of surface cracking when bent over a mandrel were observed. Taken together, these two observations suggest that the membranes are aging very well and are in line with the requirements outlined in ASTM D6878.

Solar reflectance data were largely in line with published three-year aged values from the CRRC. This suggests that the generally held assumption that the three-year data are indicative of long-term solar reflectance is correct. Therefore, where that value is used to model building energy efficiency and/or specify HVAC equipment sizes as a result of membrane choice, the membrane is performing to long-term expectations.

> The data collected for the 20 aged TPO roofs evaluated suggest that the membranes are performing well. There were no geographical differences noted, and the results indicated that the roofs are capable of achieving their expected service lives.

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SPRI Wind Design Standard for Roofing Assemblies Is Reaffirmed

The Single-Ply Roofing Industry (SPRI) has reaffirmed ANSI/SPRI WD-1, *Wind Design Standard Practice for Roof Assemblies*. It was previously revised and affirmed in 2014. The standard was developed as a reference for the design, specification, and installation of nonballasted single-ply roof systems. It provides methodology for selecting an appropriate roof system to meet the wind uplift pressures calculated in accordance with ASCE 7-16, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*.

Download the standard here: https://www.spri.org/download/ansi-spri_standards_2020_restructure/wd-1/ANSI-SPRI-WD-1-2020-Wind-Design-Standard-Practice-for-Roofing-Assemblies.pdf.