Performance Analysis of Aged TPO Membranes

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ABSTRACT

New thermoplastic polyolefin (TPO) roof membranes have been extensively analyzed in laboratories, in roof farm fields, and under accelerated weathering conditions. The ASTM International material standard for TPO membranes has been improved since its inception to incorporate more demanding tested-product performance, including requirements for accelerated weathering and aging.

Industry data on the aged performance of TPO roof membranes to date have largely been based on laboratory work, regional studies (such as the ten-year study by the Western States Roofing Contractors Association (WSRCA), and anecdotal case studies of field-installed TPO roofs—predominantly those that have been improperly designed and/or installed, and membranes with formulations that resulted in premature failure.

Today, there are TPO roofs in the U.S. that have been in service for nearly 20 years. This paper will review the long-term performance of a large sampling of field-aged TPO roof membranes installed throughout the U.S. by evaluating thickness, flexibility, inspection under 7x magnification, and aged seam and repair weld adhesion. The intent of this study is to evaluate 1) field-aged TPO roof membrane performance and 2) the ability to repair field-aged TPO roof membranes.

SPEAKER

Jennifer Keegan is the director of building and roofing science for her firm, focusing on overall roof system design and performance. Keegan has over 20 years of experience as a building enclosure consultant specializing in assessment, design, and remediation of building enclosure systems. She provides technical leadership within the industry as the chair of the ASTM D08.22 Roofing and Waterproofing Subcommittee, and she serves as an advocate for women within the industry as the educational chair for National Women in Roofing and a board member of Women in Construction.

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INTRODUCTION

Thermoplastic polyolefin (TPO) roof membrane is the fastest-growing commercial roof membrane on the market and has grown significantly over the past 20 years to represent nearly 50 percent of installed low-slope roofing in the U.S. These membranes are regarded as a mature technology with proven performance defined by the ASTM International material standard for TPO membranes, ASTM D6878, *Standard Specification for Thermoplastic Polyolefin Based Sheet Roofing*. This standard has been improved since its inception to incorporate more demanding tested-product performance, including stronger requirements for accelerated weathering and aging.

TPO membranes have been extensively analyzed in laboratories and under accelerated weathering conditions.[1] This work has demonstrated the ability of TPO to provide good heat aging performance and ultraviolet (UV) stability. Data have been collected through regional studies[2] and anecdotal case studies of field-installed TPO roofs[3]—predominantly those that have been improperly designed and/or installed, and membranes with early formulations that resulted in premature failure.

Today, there are TPO roofs in the U.S. that have been in service for over 20 years.[4] As single-ply systems provide no inherent redundancy, their watertightness depends on the mechanical performance of the materials and the welded seams, together with the weathering resistance of the polymer. The real-world performance of any roof membrane also depends on the quality of the installation, maintenance, and ability to repair the membrane.

This paper reviews the long-term performance of field-aged TPO roof membranes installed throughout the U.S. to assess performance and the ability to repair aged TPO roof membranes. This is an ongoing effort, and to date, membrane samples from 20 roofs across the U.S. have been analyzed. Specifically addressed are known failure modes of some manufactured TPO membranes, which include erosion of the cap (thickness over scrim) down to the scrim and surface cracking, as well as concerns surrounding the repairability of TPO membranes as they age.

HISTORY

TPO membranes have been in use in Europe since the 1960s. It wasn't until the late 1990s and early 2000s that TPO membranes began to gain market share in the U.S. ASTM standard specification development began in the early 1990s, and it took over 10 years and 36 drafts before a consensus was reached. The first TPO standard specification was published in 2003: ASTM D6878. The standard prescribes various dimensional and physical properties, as well as compositional and accelerated aging requirements.

Given early examples of premature aging of some TPO membranes—especially those adjacent to highly reflective surfaces or with a buildup of dark dust and debris—the industry had a vested interest in the continual advancement of the ASTM standard. Over the past 15 years, ASTM D6878 has been enhanced four times.

- In 2006, the UV exposure requirement was doubled from 5,040 kJ/m^2 to 10,080 kJ/m^2.
- In 2011, the heat aging requirement was increased from 4 weeks to 32 weeks at 240°F. The thickness over scrim specification was also changed from a minimum of 16 mils, regardless of total thickness, to a minimum of 30% of the total membrane thickness.
- In 2017, the heat aging requirement was changed to 32 weeks at 240°F or 8 weeks at 275°F. In addition, the retention of physical properties requirement was deleted and a specification that weight change be <1.5% after heat aging was added.
- In 2019, the standard was yet again strengthened to specifically identify the sampling procedures for heat aging. The exposures and pass/fail criteria were not modified.

As single-ply systems provide no inherent redundancy, their watertightness depends on the mechanical performance of the materials and the welded seams, together with the weathering resistance of the polymer. The real-world performance of any roof membrane also depends on the quality of the installation, maintenance, and ability to repair the membrane.

Figure 1 – Typical 2- x 3-ft. field sample.

Figure 2 – Typical north parapet, 30 inches in height.

Field studies have been conducted to evaluate the long-term performance of TPO roof membranes. A European study examined three in-situ TPO roofs that had up to 12 years in service.[5] All the roofs were found to be performing well with no issues or change in membrane thickness. The peel and shear resistance values of seams obtained from the field samples were similar to or higher than nominal values required by Standards UNI EN 12316-2 and EN 12310-1 and 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 core 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 June of 2011,[6] and evaluated 60-mil mechanically attached, white TPO membranes from four manufacturers in four distinctly 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 aging, in combination with a potentially less robust TPO formulation, noting 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." Given this observation and concerns within the industry on how successfully aged TPO will be repaired and maintained, this study evaluated how aged TPO membranes are performing and the integrity of repairs to these aging membranes.

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 U.S. that were at least 12 years in service. Roofs were selected to gain a general sense of typical performance in various locations across the country. Access and availability of the owner were governing factors.

Most of the roofs evaluated to date in this study were installed between 2005 and 2006; the oldest sample reviewed to date was installed 19 years ago in 2001. All samples were from the same manufacturer and were predominantly 45- and 60-mil smooth-back membranes. Samples were taken from mechanically attached, induction-welded, and adhered roofs. Self-adhered membranes were excluded from this study.

Sample Selection

Two samples were taken from each roof. Each sample was 2 by 3 ft. and captured a field-welded seam. One sample was taken from the field of the roof (see *Figure 1*), and the other was taken in a location that resulted in increased heat exposure (see *Figure 2*). To date, the increased heat-exposed samples were located adjacent to the north parapet wall. In the future, this ongoing study will include areas where sunlight reflects off adjacent glazing or metal.

The large samples were cut into smaller pieces to evaluate membrane thickness, thickness over scrim, brittleness, 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 location on the roof.

Test Program

The testing program was built around ASTM D6878-19, with modifications as needed for aged samples. The artificial aging tests were replaced with field aging for a minimum of 12 years. All tests were conducted in a commercial test laboratory. All data gathered were used in the analysis.

Membrane Thickness and Thickness of Coating Over Scrim

TPO membranes consist of two polymer layers of TPO—the cap and the core—which are laminated together with a polyester reinforcing scrim in between. Following ASTM D751[7] and D7635/D7635M,[8] respectively, the overall membrane thickness and the thickness of the coating over the scrim (or cap layer) were measured. These measurements were compared to the current ASTM TPO standard requirements for new membranes to evaluate how they were weathering.

Heat Aging and Weather Resistance

ASTM D6878-19 requires 56 days of heat aging or a radiant exposure of 10,080 kJ/(m^2 nm) prior to the mandrel bend and inspection. As the membrane samples were already aged, the artificial UV and heat aging exposures were eliminated from the test protocol, and the pass/fail requirements were applied to the field-aged materials.

Heat aging and weather resistance are evaluated per ASTM D573[9] and ASTM G151/G155,[10] respectively, which include an inspection at 7x magnification when bent over a 3-inch mandrel for surface cracking.

Low-Temperature Flexibility

Low-temperature flexibility or the brittleness point was evaluated per ASTM D2137, method B.[11] The specimens 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 cover board or insulation facer were adhered to the membrane core. This rendered the specimens too stiff to adequately test.

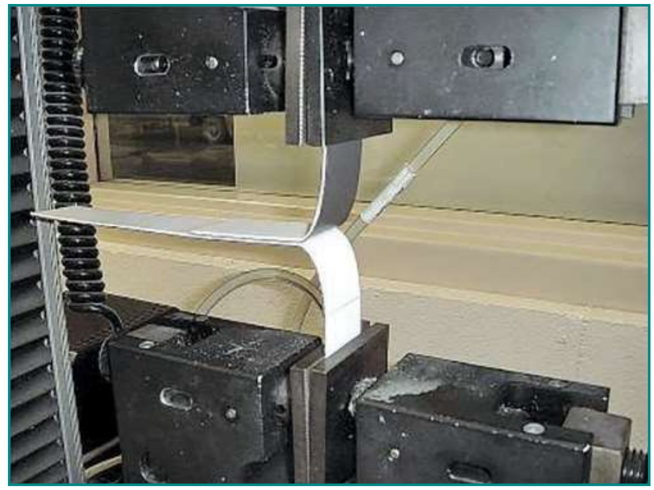

Figure 3 – The ply adhesion test in progress.

Aged Ply Adhesion

ASTM D1876[12], also referred to as the T-Peel Test, was used to evaluate the welded seam ply adhesion. The ply adhesion of the aged weld was tested, as shown in *Figure 3*. 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 is calculated by averaging the load during the first five delamination events.

Ply adhesion testing of a proper weld will fail cohesively, exposing the underlying scrim. This is called a "film tearing bond" and is also used to evaluate 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, indicating a complete and proper weld.

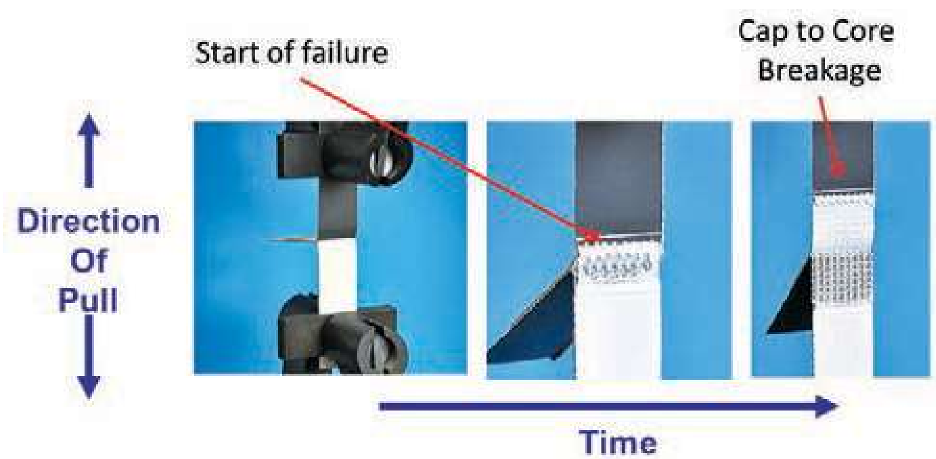

Figure 4 – Illustration of the ply adhesion test and a full film tearing bond, indicating a complete weld.

Figure 5 – To date, samples have been collected from 20 roofs across the U.S.

Repair Ply Adhesion

New TPO membrane, which was commensurate in type and thickness of the existing membrane, was welded to the aged membrane to evaluate the ability to repair aged materials. Repairs with new membrane welded to the cap of the aged membrane were evaluated, as well as new material welded to the core (the underside) of the aged membrane. Ply adhesion to the core was not evaluated for adhered membrane 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.

DATA ANALYSIS

Samples were taken from 20 different roofs across the U.S. (see *Figure 5*). These roofs were installed over office buildings, manufacturing facilities, retail outlets, libraries, automotive repair shops, warehouses, and a grocery store. All data gathered were used in the analysis.

On average, a typical roof membrane in this study was installed between 2005 and 2006, had been exposed to 20 hailstorms, over 50 ft. of rain, over 500 days of 90°F+ temperatures, and wind gusts of up to 92 mph (*Figure 6*).

Specifically, the roof membrane from Orlando, FL, had been exposed to the elements for over 17 years. This roof had weathered 9 hurricanes, 13 hailstorms, 56 ft. of rain, 1,660 days of 90°F+ temperatures, and wind gusts of up to 105 mph.

Membrane Thickness and Thickness of Coating Over Scrim

Retention of the cap material (i.e., the thickness over scrim) is critical to the membrane's long-term performance, as it provides the UV and heat stabilization properties of the membrane. As the cap erodes, the scrim can become exposed and the weathertightness of the membrane is then compromised, as shown in *Figure 7*.

The analysis of aged roof samples began with overall membrane thickness. ASTM Standard D6878-19 requires the as-produced membrane to be within +15%, -10% of stated thickness, and not less than 39 mils. Even after 12 or more years of aging, all of the 45- and 60-mil membrane samples complied with the current ASTM requirements for newly manufactured TPO membranes, as shown in *Figure 8*.

ASTM Standard D6878-03, the active specification at the time the sampled roofs were installed, required 12-mil thickness over scrim. The current version of this standard requires the thickness over scrim to be at least 30 percent of the overall membrane thickness and not less than 18 mils. Both the 45- and 60-mil membranes analyzed in this study are still in compliance with the newly manufactured membrane requirements and are even in compliance with the current ASTM Standard D6878-19, with the thickness over scrim exceeding ASTM minimums and averaging 37 to 40 percent of the nominal membrane thickness. The 45-mil samples averaged 18 mils over scrim and the 60-mil samples averaged 22 mils over scrim. Representative data are shown in *Figure 8*.

Weather Exposure over the Life of Each Membrane

Location	Age of roof	# hail storms	Amount of rain	Days over 90°F	Wind gusts up to
Pennsauken, NJ	15 yrs	11	57 ft	468	85 mph
Philadelphia, PA	14 yrs	11	48 ft	230	56 mph
Lake St. Louis, MO	13 yrs	39	41 ft	644	120 mph
Oak Lawn, IL	13 yrs	25	41 ft	239	100 mph
Berea, KY	14 yrs	13	55 ft	456	95 mph
Charlestown, SC	13 yrs	28	61 ft	1,067	98 mph
Atlanta, GA	13 yrs	16	54 ft	755	90 mph
Orlando, FL	17 yrs	13	56 ft	1,660	105 mph

Figure 6 – Representative weather exposure over the life of the roof membrane prior to collection. Data provided by Accuweather Enterprise Solutions, specific for this study.

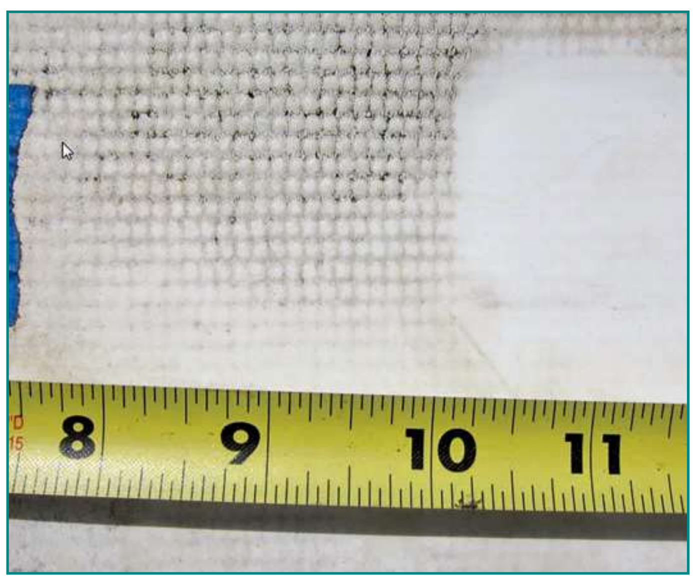

Figure 7 – Premature failure as cap erodes and exposes scrim. Image courtesy of René Dupuis.

Heat Aging and Weather Resistance

Surface cracking was evaluated by visual inspection of the roof membranes at the time the samples were collected, and through modified versions of heat aging and weather-resistance testing. Both ASTM tests require inspection at 7x magnification when bent over a 3-in. mandrel. As the samples were field aged for a minimum of 12 years, artificial heat aging and weathering were eliminated, and a focus was placed on visual assessment. This evaluation is an important indicator of long-term performance.[13] Surface cracking can lead to quick deterioration of the membrane and is a good indicator of long-term performance concerns, as indicated in *Figure 9*. All of the samples—both the 45- and 60-mil membranes—exhibited no signs of cracking when bent over the mandrel and viewed at 7x magnification.

60-mil white TPO				
Location	Thickness over Scrim	Total Thickness	% of thickness	Meets ASTM D6878
Bergenfield, NJ	25 mils	57 mils	94%	✓
Atlanta, GA	20 mils	57 mils	94%	✓
Berea, KY	26 mils	55 mils	92%	✓
Pennsauken, NJ	26 mils	56 mils	93%	✓
Orlando, FL	22 mils	55 mils	92%	✓
45-mil white TPO				
Location	Thickness over Scrim	Total Thickness	% of thickness	Meets ASTM D6878
Atlanta, GA	20 mils	44 mils	97%	✓
Philadelphia, PA	17 mils	43 mils	95%	✓
Lake St. Louis, MO	18 mils	44 mils	98%	✓
Oak Lawn, IL	18 mils	44 mils	99%	✓
Charlestown, SC	18 mils	45 mils	100%	✓

Figure 8 – Representative thickness and thickness over scrim data for 60- and 45-mil membranes. ASTM D6878-19 requires the thickness over scrim to be at least 30 percent of the overall membrane thickness and not less than 18 mils for 60-mil membrane or 15 mils for 45-mil membrane.

Low Temperature Flexibility

The aged roof samples were evaluated for low temperature flexibility to determine whether the membrane became more brittle and prone to cracking as it aged. ASTM Standard D6878-19 requires new membranes to have a brittleness point of -40°F or lower. All of the 60-mil samples tested to date still met this requirement after 12 or more years of field aging. The 45-mil samples showed signs of cracking at -35°F, as shown in *Figure 10*. While this is still good performance and aged membranes cannot be expected to perform at the same level as new membranes, the data do support the use of thicker membranes for longer-term performance.

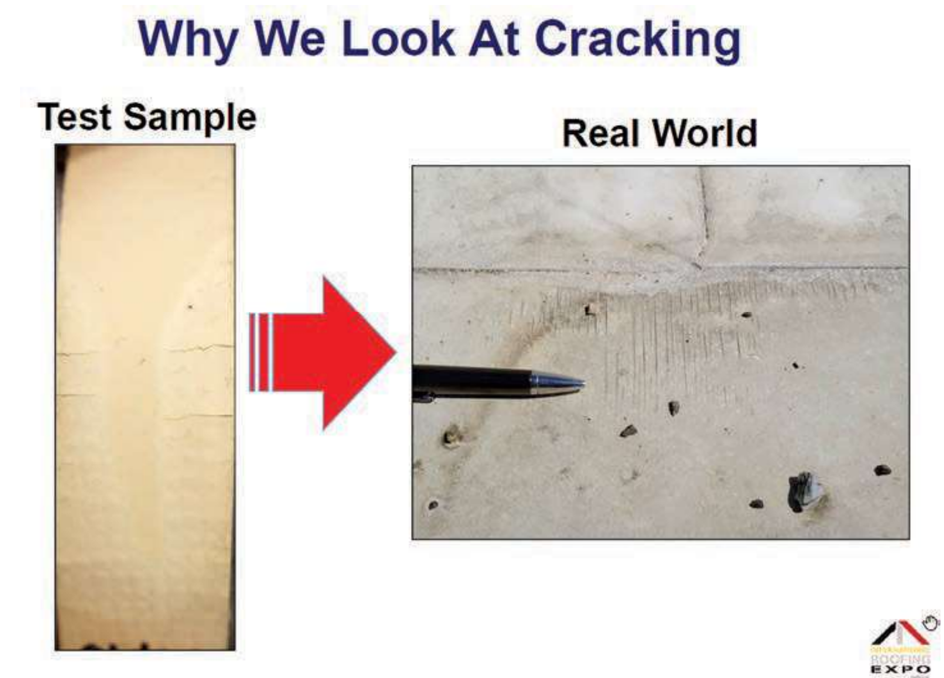

Figure 9 – Prior testing performed by René Dupuis illustrates the reason why we look at cracking of the membrane. The test sample is from laboratory exposure and the real-world sample is from an aged roof (not directly related to this study).

Aged Ply Adhesion and Repair Ply Adhesion

The ply adhesion of the aged samples averaged approximately 50 lbf/in. for both the 45- and 60-mil membranes, with a minimum of 70 percent film tearing bond. Representative data are shown in *Figure 13*. Ply adhesion of TPO membranes should be evaluated throughout the day during installation. The film tearing bond sample is evaluated to confirm that 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 must adjust the heat and/or speed at which the welding equipment is being used. While failures associated with welded seam delamination are not widespread, ply adhesion is used as a quality control tool in the field. However, there is not a clear industry consensus on the minimum strength requirement to evaluate ply adhesion.

New TPO membrane samples included in a broad TPO sampling study of all industry manufacturers conducted by Structural Research, Inc. (SRI)[14] averaged a

60-mil white TPO			45-mil white TPO		
Location	Low Temp Flex	Meets ASTM D6878	Location	Low Temp Flex	Meets ASTM D6878
Bergenfield, NJ	-40°F	✓	Atlanta, GA	-35°F	
Atlanta, GA	-40°F	✓	Philadelphia, PA	-35°F	
Berea, KY	-40°F	✓	Lake St. Louis, MO	-35°F	
Pennsauken, NJ	-40°F	✓	Oak Lawn, IL	-35°F	
Orlando, FL	-40°F	✓	Charlestown, SC	-35°F	

Figure 10 – Representative low temperature flexibility data for 60- and 45-mil membranes. ASTM D6878-19 requires new membranes to have a brittleness point of -40°F or lower.

Figure 11 – Repair of aged TPO membrane with a new patch welded to the aged cap. Image courtesy of WSRCA.

Figure 12 – Repair of aged TPO membrane with a new patch welded to the aged core. Image courtesy of WSRCA.

ply adhesion (T-peel) value of 40 lbf/in., with a minimum value of 29.3 lbf/in. However, previously, Simmons et al.[15] found that the ply adhesion tests typically failed adhesively—meaning there was not a strong bond between the TPO layers—when the ply adhesion was 26 lbf/in. or less. Simmons's findings support SRI's minimum value threshold for ply adhesion.

The ply adhesion values of the aged TPO membranes were 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.

To address questions around the ability to repair aged TPO membranes, this study examined the adhesion of new membrane to aged membrane. Two approaches were examined: welding the new membrane to the cap of the aged membrane (see *Figure 11*), and welding new membrane to the core of the aged membrane (see *Figure 12*).

The ply adhesion of the new membrane to the aged cap averaged 43 lbf/in. for 45-mil membranes and 47 lbf/in. for 60-mil membranes. For the new membrane welded to the aged core, the ply adhesion averaged 53 lbf/in. and 57 lbf/in. for the 45-mil and 60-mil membranes, respectively. Representative data are shown in *Figure 13*.

The ply adhesion values of new repair membrane to the aged TPO membrane are above the average ply adhesion value of 40 lbf/in. from the SRI study on new TPO membranes. This provides validity to the integrity of repairs to aged TPO membranes and the ongoing maintainability of these roofs.

NEXT STEPS AND INTERIM CONCLUSIONS

While this paper summarizes data from 20 different roofs from around the country, more evaluations are underway. Samples will continue to be collected from roofs across the U.S., with the intent of having a fair representation in the majority of the climate zones. The authors will continue to analyze data and look for trends between climate zones, exposure, membrane thickness, application method, and more as data become available.

60-mil white TPO

Location	Aged ply adhesion	Film tearing bond	Repair ply adhesion to cap	*Repair ply adhesion to core
Bergenfield, NJ	45.1	82%	57.2	N/A
Atlanta, GA	59.7	89%	46.7	N/A
Berea, KY	54.3	98%	58.9	58.5
Pennsauken, NJ	59.3	78%	55.0	69.1

45-mil white TPO

Location	Aged ply adhesion	Film tearing bond	Repair ply adhesion to cap	*Repair ply adhesion to core
Atlanta, GA	52.5	88%	46.8	N/A
Philadelphia, PA	52.0	86%	48.3	66.2
Lake St. Louis, MO	56.3	95%	50.8	56.2
Oak Lawn, IL	47.9	70%	47.9	62.1
Charlestown, SC	51.7	98%	40.3	57.1

Ply adhesion values are presented in lbf/in
*Ply adhesion to the core was not evaluated for adhered roof systems

Figure 13 – Representative ply adhesion data for 60- and 45-mil membranes. All aged and repair ply adhesion tests exceeded the average ply adhesion value of 40 lbf/in., noted in the SRI study for new 60-mil TPO membranes.

To date, the increased heat exposure samples have been limited to the membrane adjacent to the north parapet wall. No measurable differences in performance between field and increased heat-exposed samples have been observed. However, it is hoped that samples that have been subjected to a harsher exposure, such as reflection from glass or metal from an adjacent building, can be located.

It is noted that all data received to date have been included in this analysis. No data—detrimental or otherwise—have been excluded from the analysis or findings.

The findings to date, as summarized in *Figure 14*, illustrate the robust performance of TPO membranes as they age. Given the inherent flexibility and fungal resistance of TPO, and the UV and heat stabilizers, this comes as no surprise. However, the ability to repair aged TPO membranes has been undefined and anecdotal to date. The interim findings of this study clearly demonstrate the weld integrity of properly executed repairs to aged TPO membranes.

60-mil white TPO	**Average**	**Performance**
Membrane Thickness	55 mils	Exceeds ASTM D6878
Thickness over Scrim	22 mils	Exceeds ASTM D6878
Low Temperature Flexibility	-40°F	Meets ASTM D6878
Heat Aging/Weather Resistance (7X Magnification mandrel bend)	Pass	Meets ASTM D6878
Aged Ply Adhesion	51 lbf/in	> Avg. ply adhesion for new TPO membrane[1]
Repair Ply Adhesion to Cap	47 lbf/in	
Repair Ply Adhesion to Core	57 lbf/in	
45-mil white TPO	**Average**	**Performance**
Membrane Thickness	18 mils	Exceeds ASTM D6878
Thickness over Scrim	42 mils	Exceeds ASTM D6878
Low Temperature Flexibility	-35°F	<ASTM D6878 (-40°F)
Heat Aging/Weather Resistance (7X Magnification mandrel bend)	Pass	Meets ASTM D6878
Aged Ply Adhesion	49 lbf/in	> Avg. ply adhesion for new TPO membrane[1]
Repair Ply Adhesion to Cap	43 lbf/in	
Repair Ply Adhesion to Core	53 lbf/in	

1. Dupuis, Rene M., "Final Report on 2013-2014 Broad Sampling TPO Test Program"

Figure 14 – Average findings from study to date for 45- and 60-mil membranes as compared to ASTM D6878-19.

In summary, the aged TPO membrane roofs in this study are performing well and, in most instances, meeting the current ASTM D6878-19 requirements for newly manufactured membranes.

- Even after 12 or more years of aging, both the 45- and 60-mil membrane samples exceeded current thickness requirements for newly manufactured TPO membranes.
- Both the 45- and 60-mil membranes analyzed in this study are still in compliance with these newly manufactured membrane requirements, with the thickness over scrim averaging over 40 percent of the actual aged membrane thickness.
- All of the samples—both the 45- and 60-mil membranes—exhibited no signs of cracking when bent over the mandrel and viewed at 7x magnification.
- All of the 60-mil samples tested to date still meet cold temperature flexibility requirements after 12 or more years of aging. The 45-mil samples showed signs of cracking at -35°F. While this is still good performance and aged membranes cannot be expected to perform at the same level as new membranes, the data support the use of thicker membranes for longer-term performance.
- Ply adhesion values of the aged TPO membrane were 15 percent above the average ply adhesion value from the SRI study on new TPO membranes. As expected, the aged welds appear to be performing well and are of adequate strength.
- Ply adhesion values of new repair membrane to the aged TPO membrane are above the average ply adhesion value for new TPO membranes. This provides some validity to the integrity of properly executed repairs to aged TPO membranes.

While this paper summarizes data from 20 different roofs from around the country, more evaluations are underway. Samples will continue to be collected from roofs across the U.S., with the intent of having a fair representation in the majority of the climate zones.

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