Correlating Accelerated Laboratory, Field, and Thermal Aging TPO Membranes

ABSTRACT: Thermoplastic polyolefin (TPO) roofing membranes have been used in the US low-slope roofing industry as single-ply membranes for over 15 years, and have seen widespread acceptance. TPO membranes have been defined by ASTM Standard D6878-08, “Standard Specification for Thermoplastic Polyolefin Based Sheet Roofing,” Annual Book of ASTM Standards, Vol. 04.04, ASTM International, West Conshohocken, PA, 2008, www.astm.org, which sets a minimum threshold for accelerated weathering performance. To be ASTM D6878 compliant, a TPO membrane shall not show any visual micro-cracking under 7X magnification after being exposed in a xenon arc light apparatus to a minimum irradiance of 10 080 kJ/m² at 340 nm. While the ongoing development of TPO membranes uses D6878 as the basic standard, it is necessary for individual membrane manufacturers to develop an advanced understanding of TPO long-term weathering durability to further improve confidence in the expected service life. In this paper, a novel ultra accelerated outdoor weathering technique, atlas ultra accelerated weathering system (UAWS), is used to predict long-term weathering durability performance of TPO. The comparison and correlation of this novel technique with other artificial accelerated weathering methods, such as xenon arc light [ASTM G155-05a, “Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials,” Annual Book of ASTM Standards, Vol.14.04, ASTM International, West Conshohocken, PA, 2005, www.astm.org] and fluorescent UV light [ASTM G154-06, “Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials,” Annual Book of ASTM Standards, Vol. 14.04, ASTM International, West Conshohocken, PA, 2006, www.astm.org] are shown and reviewed. The surface temperatures of TPO membranes exposed in the UAWS device as well as in the field are shown to further understand the heat impact on TPO durability. In addition, accelerated heat aging at temperatures up to 138°C are shown to give very good correlation to other aging tests.

KEYWORDS: long term weathering durability, thermoplastic polyolefin (TPO), ultra accelerated weathering system (UAWS), heat resistance, xenon arc apparatus, fluorescent UV, weathering, concentrated sunlight, flexible solar panels, flexible solar modules

Introduction

Single-ply membranes continue to gain roofing market share, with TPO being increasingly accepted as a viable option. Manufacturers typically do not significantly improve product performance of existing products, and often engage 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. Thermoplastic polyolefin has followed the latter route and has been upgraded significantly since its introduction around 15 years ago.

Thermoplastic polyolefin membranes have not suffered from systemic issues, but some problems have been experienced by individual manufacturers. The most important has been premature failure of the membrane itself, of which there have been two main types. The first is related to manufacturing defects which generally manifest themselves early in the life of a roof. An example has been the delamination of the top and bottom layers of the sheet, caused by failure to ensure 100% successful adhesion between the sheets. The second type of failure has been inadequate resistance to weathering which manifests itself as erosion of the TPO and eventual loss of water tightness.

As more TPO roofs have been installed, another type of weathering failure has started to appear. It has become clear that high temperatures can significantly accelerate the aging of TPO. Under normal
circumstances, TPO never experiences temperatures much greater than 49 to 54 °C, even in southern exposures. However, in situations where TPO becomes unusually heavily soiled, or receives both direct and indirect exposure from nearby highly reflective surfaces, it is now clear that surface temperatures can be 82 °C or higher.

Recently, with the roof becoming a platform for the solar energy generation, more photovoltaic modules, commonly known as solar panels, have been installed on TPO roofs. Rigid and flexible solar panels are the two major types. Flexible panels are made using plastic films to encapsulate the individual solar cells. They can be shipped with a peel-and-stick backing, enabling rapid installation onto a roof surface. However, the unexpected thermal loads on TPO membranes caused by dark-colored flexible solar panels during exposure to sunlight may significantly increase the surface temperature of TPO membranes.

Thermoplastic polyolefin membranes have been defined by ASTM standard D6878 [1], developed by subcommittee D08.18 on Non-Bituminous Organic Roof Coverings. It sets a minimum threshold for accelerated aging performance with respect to heat and ultraviolet light (UV) exposure. To be D6878 compliant, TPO membrane has to be exposed in a Xenon Arc apparatus for a minimum radiant exposure of 10 080 kJ/m² at 340 nm without any visual micro-cracking under 7X magnification. While ongoing development of TPO membranes uses D6878 as the base standard, it is necessary for individual membrane manufacturers to develop a more advanced understanding of TPO long-term weathering durability to further improve confidence in the expected service life.

Generally, TPO membrane comprises a cap layer (top side) and a core layer (bottom side) with a polyester scrim layer sandwiched between. Each of the cap and core layers is made of a TPO sheet but they may vary significantly in composition. When installed on the roof of a building, the cap layer of TPO membrane faces upwards towards the direction of sunlight and the core layer faces downwards towards the roof. The cap layer is formulated with TPO resins and additives, such as UV stabilizers, UV absorbers, antioxidants, process and thermal stabilizers, fire retardants, white pigments or color pigments, and any other additives. The formulation of the cap layer provides for long-term stability in an outside environment and an aesthetic appearance if containing color pigments. While the core layer may be formulated to include additives along with TPO resins, the core layer may be configured to include less or no additives to reduce costs.

Accelerated weathering tests are commonly used in evaluating polymeric materials to understand photo-degradation of the materials exposed to high UV flux [2–5]. Various studies [6–9] have discussed factors affecting service life of roofing membranes, especially single-ply membranes, such as polyvinyl chloride (PVC), ethylene-propylene-diene terpolymer (EPDM), and TPO. By using analytical methods, such as dynamic mechanical analysis (DMA), thermogravimetry (TG), and Fourier transform infrared (FTIR) spectroscopy, the effect of heat at 116 °C on specially formulated TPO films were studied [10].

In this paper, we examine the stability of TPO towards ultraviolet (UV) and thermal breakdown. This work uses a wide range of accelerated aging and weathering tests, to show how commercially available TPO membranes perform. The focus of the work was on the physical integrity of the membrane and the evaluation is not intended to be a mechanistic or chemical study of TPO degradation. The tests are reviewed in detail and their relevance is discussed.

**Experimental**

**TPO Membrane Samples**

A total of 13 commercially available TPO membranes were obtained for this study. The manufacturing date codes covered the second half of 2008 and the first half of 2009. The samples were 1.14 mm, 1.52 mm, and 2.03 mm in thickness, with all suppliers being represented by at least two thicknesses. One set of samples was from a supplier that no longer directly manufactures TPO.

**Test Roof Set Up**

A test system of 11 Uni-Solar [11] flexible solar peel and stick panels was installed over TPO on a facility in Gainesville, TX as shown in Fig. 1. The solar panels were installed in accordance with the manufacturer’s guidelines and were wired to a grid connected inverter.
The existing roof was a white TPO membrane. On top of the existing roof, 0.61 ms wide strips of four colored TPO membranes, such as white, light gray, dark gray, and blue, were attached. A total of 36 thermocouples were placed at the following three locations with three duplicates for each colored TPO membrane.

- Location A: TPO membrane surface 0.91 ms away from solar modules.
- Location B: TPO membrane surface which is 12.7 mm gap area between two solar modules.
- Location C: sandwiched between the solar modules’ black edge and TPO membrane.

**Durability Tests**

*Accelerated Weathering with a Xenon Arc Apparatus*—An Atlas Ci4000 Xenon Weather-Ometer was used to carry out the accelerated weathering test. This was conducted in accordance to ASTM D6878 and ASTM G155 [12]. Exposure conditions were as follows:

1. Lamp Type: Xenon Arc.
2. Filter Type: Daylight.
3. Irradiance: 0.35 to 0.70 W/m² at 340 nm.
4. (42 to 84 W/m² at 300 to 400 nm).
5. Cycle: 690 min light, 30 min light plus water spray.
7. Chamber Air Temperature: 50 ± 2 °C.
8. Relative Humidity: 50 ± 5%.
10. Specimen Rotation: Refer to ASTM G 155.
11. Radiant Exposure: 10 080 kJ/m² at 340 nm.

In the previous version of D6878-03, the radiant exposure requirement was 5040 kJ/m², versus the present requirement of 10 080 kJ/m². However, although the exposure was less, there was an additional requirement that the samples retain 90% of the original breaking strength and elongation at reinforcement break. This doubling of the exposure requirement was a recognition that the lifetime expectations for TPO membranes are increasing. Also, the eventual failure mode was not expected to be strength-related but rather cracking and erosion of the surface to the point that a breach would occur through the entire membrane.

*Accelerated Weathering Test with Fluorescent UV Light*—Based on ASTM G154 [13], the test method was modified to expose TPO membranes in accordance with the following exposure conditions.

3. Irradiance: 1.55 W/m² at 340 nm.
5. Black Panel Temperature (BPT): 80 ± 3 °C.
6. Relative Humidity: 0 ± 5%.
7. Spray Water: Deionized.

Heat Aging—Per ASTM D6878, the heat aging requirement of TPO membranes is 90% tensile strength retention after aging at 116 °C for 670 hs. However, all available commercial membranes pass that requirement despite the fact that there have clearly been heat-related failures. For this work, TPO samples were held at 138 °C, 116 °C, and 93 °C until cracking was observed under 7X magnification. The test method was as follows:

1. Set up temperature as specified using a forced air oven which is well calibrated.
2. Put 25.4 mm X 69.9 mm piece of TPO membrane into the oven.
3. After oven aging for a time period, take the sample out of the oven and cool it to room temperature.
4. Wrap the sample around a 76.2 mm mandrel to examine the TPO cap layer side to see if there are visible cracks under 7X magnification.
5. If there are visible cracks under 7X magnification, record the number of days of exposure inside the oven.

Accelerated Weathering Test with Fluorescent UV Light Followed by Heat Aging—First, TPO samples were exposed to fluorescent UV light for 2500 – 5500 hrs per test condition described in Method 2. After 2500–5500 hrs exposure, the TPO samples not showing micro-cracking under 7X magnification were put into 138 °C oven for further heat aging. The same procedures as described in Method 3 were followed to record the number of days taken for those samples to display micro-cracking under 7X magnification.

Accelerated Outdoor Weathering Using Concentrated Natural Sunlight—An issue with laboratory-based accelerated Xenon Arc weathering is that the light sources used do not perfectly replicate the solar spectrum. Therefore, this technique uses accelerated outdoor aging, where the sun’s light is multiplied through the use of mirrors [14].

In the example shown, an accelerated outdoor aging study program was set up with Q-Lab Corporation in Buckeye, AZ for 3–4 years. It is Q-Trac natural sunlight concentrators with water spray cycles per ASTM G 90 [15], also called EMMAQUA test (equatorial mount with mirrors for acceleration with water), is used to simulate southern Florida exposures.

The natural sunlight concentrator automatically tracks the sun from morning to night with solar sensors adjacent to the test specimens mounted on a target board. A series of ten highly reflective mirrors reflect and concentrate full spectrum natural sunlight onto the test specimens. With the maximized amount of sunlight exposure received by the test specimen, this tracking solar concentrating system allows product weathering evaluation in a greatly reduced time period. Also, since the light source is natural sunlight, there is less concern over whether the simulated light matches sunlight than is the case for the Xenon Arc apparatus. The outdoor system is shown in Fig. 2.

FIG 2.—Natural sunlight concentrator (The sunlight is reflected/concentrated by ten mirrors directly to the target sample board).
The solar energy tracking device shows that about 1420 MJ/m² total ultraviolet radiation (TUV) is focused annually on the samples. This is about the same amount of UV deposited over five years of Florida (1400 MJ/m²) or 4.25 years of Arizona exposure (1665 MJ/m²). Table 1 shows TUV of FL versus AZ. Figure 3 shows irradiance level of Miami Sunlight versus natural sunlight concentrator.

Ultra Accelerated Outdoor Weathering Test (UAWS)—To increase the concentration of sunlight onto a specimen, thereby shortening the necessary exposure time, the ultra accelerated weathering system (UAWS) [16] was used. This was developed by national renewable energy laboratory (NREL) together with collaborators at the Institute of Laser Optic Technology in Moscow, and Atlas Material Testing Technology. The UAWS has an array of 29 reflective facets. Each facet has a 96 layer vacuum deposited coating on the surface, which concentrates the UV portion of natural sunlight and attenuates most of the visible and near infrared portions of the solar spectrum. The 29 facets collect sunlight and reflect the UV portion of the solar spectrum onto the target area holding the samples, which are on an arm about 3.05 ms away from the array of facets. The UAWS is shown in Fig. 4.

UAWS is capable of collecting approximately 17 000 MJ/m² Total Ultraviolet Radiation (TUV) annually in Arizona. It is about the same amount of UV deposited over 60 years of Florida exposure (16 800 MJ/m²). In the example shown, the UAWS was operated by the Atlas Material Testing Technology in Phoenix, AZ.

Results and Discussion

TPO Membrane Failure Indication

Of critical importance in any study of membrane performance is the parameter(s) that best indicates membrane degradation. Thermoplastic polyolefin studies elsewhere [8,10] have used a variety of physicochemical techniques. In the first phase of this study, three types of weathering test techniques, xenon arc

<table>
<thead>
<tr>
<th>Years</th>
<th>FL</th>
<th>AZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>280</td>
<td>333</td>
</tr>
<tr>
<td>2</td>
<td>560</td>
<td>666</td>
</tr>
<tr>
<td>3</td>
<td>840</td>
<td>999</td>
</tr>
<tr>
<td>4</td>
<td>1120</td>
<td>1332</td>
</tr>
<tr>
<td>5</td>
<td>1400</td>
<td>1665</td>
</tr>
</tbody>
</table>

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| FIG 3.—A comparison of irradiance versus wavelength for natural sunlight concentrator (Q-Trac) and miami summer daylight.
apparatus, concentrated sunlight, and long-term real life field exposure in Tampa, FL, were employed to test a white TPO membrane, 1.14 mm thickness membrane, for long-term durability. The tensile strength of the tested white TPO membrane was measured against the tensile strength of the unaged sample. The % retained tensile strength was then calculated and the results after various lengths of exposure are summarized in Table 2.

The data shows that, regardless of the weathering test, microcracking corresponds to a retained tensile strength of approximately <92%. Due to the lack of sensitivity of this test to changes plus it is destructive nature, it was decided to use the onset of microcracking as the key indicator of membrane aging for all subsequent work. It should be noted that widespread cracking of the membrane, such that the scrim was readily exposed, normally occurred very rapidly thereafter. Since water tightness is one of the major measures of membrane integrity, cracking was therefore the key focus.

**TPO Surface Temperatures When Installed with Flexible Solar Modules**

With the test roof setup shown in Fig. 1, surface temperatures of four different colored TPO membranes were monitored continuously from June to July 2009 in Gainesville, TX. Maximum surface temperature of each colored TPO membrane for June 23rd, 2009 was measured at three different locations as follows:

Location A: At 91 cm away from the solar modules; the maximum surface temperature of the membrane is inversely linearly proportional to the membrane’s initial solar reflectance as shown in Fig. 5. As expected, for white TPO the maximum surface temperature did not exceed 54 °C.

<table>
<thead>
<tr>
<th>Weathering Test</th>
<th>Weathering Time</th>
<th>TUV (MJ/m²)</th>
<th>Florida Equivalent Sun Years</th>
<th>% Retained Tensile Strength</th>
<th>7X Micro-cracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon Arc Apparatus</td>
<td>6000 hrs (~8 months)</td>
<td>907</td>
<td>NA</td>
<td>94%</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>8000 hrs (~11 months)</td>
<td>1210</td>
<td>NA</td>
<td>82%</td>
<td>Yes</td>
</tr>
<tr>
<td>Concentrated Natural Sunlight</td>
<td>4 Years</td>
<td>5680</td>
<td>20 Years</td>
<td>89%</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>3 Years</td>
<td>4260</td>
<td>15 Years</td>
<td>91%</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>2 Years</td>
<td>2840</td>
<td>10 Years</td>
<td>96%</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>1 Year</td>
<td>1420</td>
<td>5 Years</td>
<td>96%</td>
<td>No</td>
</tr>
<tr>
<td>Real Life Field Exposure, South Florida (Tampa test deck)</td>
<td>5 Years</td>
<td>1400</td>
<td>5 Years</td>
<td>98%</td>
<td>No</td>
</tr>
</tbody>
</table>
Location B: In the 1.27 cm gap area between two solar modules, the maximum surface temperature of the white TPO membrane in this area was as high as 77 °C.

Location C: At the sandwiched area between the solar module’s black edge and TPO membrane, the maximum surface temperature of white TPO reached around 92 °C. Note that the membrane only experienced heat in this area, with light and UV being blocked by the panel. As is expected in this case, the solar reflectance of colored TPO membrane played no role in determining the temperature.

Maximum surface temperatures of TPO membranes at the three locations are shown in Table 3. On June 23, 2009, the daytime weather of Gainesville, TX was sunny with 47 °C maximum ambient air temperature and it gave the highest TPO measured temperatures. Table 3 also shows the solar reflectance of the each colored TPO membrane.

Figure 6 shows the maximum surface temperatures of white TPO membranes with respect to the above three locations over the period of June 8, 2009 to July 19, 2009 in Gainesville, TX.

Heat Aging Studies

Having established that peel-and-stick solar modules can potentially cause localized heating of TPO membranes far greater than the normally recommended service temperature, this section examines heat aging specifically.

As described earlier, TPO membrane samples were exposed in forced air ovens to a range of temperatures. Thirteen of the samples were periodically observed under 7X magnification for surface micro-cracking. Micro-cracking is a simple and clear indication of the beginning of a loss in integrity of the membrane. Other physical properties, such as tensile strength, may be useful but require extremely large samples sets due to their destructive nature. The intent of this study was to enable comparison to actual roof top observations.

<table>
<thead>
<tr>
<th>TPO Membranes (1.52 mm Thickness, Four Colors)</th>
<th>Location A: TPO Membrane (~0.914 Meters Feet Away from Solar Films) °C</th>
<th>Location B: TPO Membrane (12.7 mm Gap Area Between Two Solar Films) °C</th>
<th>Location C: Sandwiched Between Flexible Solar Modules (at Black Area) &amp; TPO Membrane °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Gray</td>
<td>0.08</td>
<td>87</td>
<td>92</td>
</tr>
<tr>
<td>Regal Blue</td>
<td>0.25</td>
<td>79</td>
<td>88</td>
</tr>
<tr>
<td>Light Gray</td>
<td>0.40</td>
<td>70</td>
<td>77</td>
</tr>
<tr>
<td>White</td>
<td>0.76</td>
<td>54</td>
<td>77</td>
</tr>
</tbody>
</table>

FIG. 5—Correlation between maximum surface temperature and solar reflectance of TPO membranes (0.914 ms away from the area of solar panels).
Table 4 shows the numbers of days taken for TPO membrane cap cracking to occur during heat aging at 138 °C and 116 °C. It should be noted that the data suggests that there is no effect of thickness. This suggests that thermal aging of these membranes is a bulk phenomenon, unlike; for example, UV aging which is more of a surface effect. Good correlation between 138 °C and 116 °C oven aging was derived as shown in Fig. 7. Clearly, 138 °C oven aging is the fastest way to study heat resistance of TPO membranes. Prediction shows that it will take over two years for the membranes with the best heat resistance to show cap cracking if 116 °C oven aging is used. As shown in Table 3, the maximum surface temperature of white TPO membrane underneath the black area of a flexible solar module can reach up to about 93 °C.

By assuming that TPO membrane is exposed to 93 °C heat loading for 6 hs per day, the number of years that TPO membranes survive in 93 °C heat only field exposure are predicted in Table 4. The better heat resistance in 138 °C heat aging, the longer the TPO membrane will last under high heat environments. The latter could arise due to the presence of a peel and stick solar module, a large amount of dirt and debris, or any other situation which increases the thermal load.

TABLE 4—Heat aging test of commercial white TPO membranes.

<table>
<thead>
<tr>
<th>TPO Membrane Samples (Thickness)</th>
<th>Oven Aging</th>
<th>Actual Days to Cap Cracking</th>
<th>Predicted Days to Cap Cracking</th>
<th>93 °C Field Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>138 °C</td>
<td>116 °C</td>
<td>116 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Actual Days</td>
<td>Predicted Days</td>
<td>Predicted Years</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X</td>
<td>Y</td>
<td>(Assuming Six Hrs/Day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>X</td>
<td>Y</td>
<td>@93 °C)</td>
</tr>
<tr>
<td>A, 1.14 mm</td>
<td></td>
<td>20</td>
<td>212</td>
<td>198</td>
</tr>
<tr>
<td>B, 1.14 mm</td>
<td></td>
<td>28</td>
<td>229</td>
<td>231</td>
</tr>
<tr>
<td>C, 1.52 mm</td>
<td></td>
<td>31</td>
<td>212</td>
<td>243</td>
</tr>
<tr>
<td>D, 2.03 mm</td>
<td></td>
<td>34</td>
<td>212</td>
<td>255</td>
</tr>
<tr>
<td>E, 1.52 mm</td>
<td></td>
<td>37</td>
<td>296</td>
<td>268</td>
</tr>
<tr>
<td>F, 2.03 mm</td>
<td></td>
<td>40</td>
<td>296</td>
<td>280</td>
</tr>
<tr>
<td>G, 2.03 mm</td>
<td></td>
<td>48</td>
<td>344</td>
<td>313</td>
</tr>
<tr>
<td>H, 2.03 mm</td>
<td></td>
<td>68</td>
<td>399</td>
<td>394</td>
</tr>
<tr>
<td>I, 1.52 mm</td>
<td></td>
<td>76</td>
<td>399</td>
<td>427</td>
</tr>
<tr>
<td>J, 2.03 mm</td>
<td></td>
<td>80</td>
<td>NA</td>
<td>443</td>
</tr>
<tr>
<td>K, 1.52 mm</td>
<td></td>
<td>85</td>
<td>473</td>
<td>464</td>
</tr>
<tr>
<td>L, 1.52 mm</td>
<td></td>
<td>187</td>
<td>NA</td>
<td>880</td>
</tr>
<tr>
<td>M, 2.03 mm</td>
<td></td>
<td>194</td>
<td>NA</td>
<td>909</td>
</tr>
</tbody>
</table>

Note: X: actual days to cap cracking @138°C oven heat aging; Y: actual days to cap cracking @116°C oven heat aging; By plotting X versus the equation of \( Y = \frac{4.0852X + 116.42}{R^2 = 0.9245} \) was derived with \( R^2 = 0.9245 \).

FIG. 6—Maximum surface temperature of white TPO membranes/flexible solar modules.
Accelerated Weathering Studies and Their Correlation

As described, 138 °C and 116 °C oven aging tests allowed the heat resistance of TPO membranes to be studied. It is equally important to understand how TPO withstands both UV and heat. As shown in Table 3, the maximum surface temperature of white TPO membrane reaches around 54 °C while being exposed 0.914 ms away from flexible solar modules. On the other hand, in the 12.7 mm gap area between two solar modules, the maximum surface temperature of white TPO membrane can reach up to 77 °C while it is exposed to sunlight at the same time.

FIG. 7—Correlation between 138 °C and 116 °C oven aging test.

FIG. 8—(a) Maximum surface temperatures of white TPO membranes exposed in two types of outdoor accelerated weathering tests, concentrated sunlight-AZ & UAWS-AZ. (b) Maximum surface temperatures of white TPO membranes exposed in two types of accelerated weathering tests with artificial lights, fluorescent UV & xenon arc.
In this study, four types of accelerated weathering methods were employed to study TPO membranes’ weathering performance under both UV and heat exposure. By comparing it with the location B of the surface temperature of white TPO membrane in the 12.7 mm gap area between two solar modules in field exposure of Gainesville, TX, Fig. 8(a) shows the maximum surface temperatures of white TPO membranes exposed to two types of outdoor accelerated weathering tests, concentrated sunlight, and UAWS, over a period of time. Figure 8(b) shows the maximum surface temperatures of white TPO membranes exposed to two types of accelerated weathering tests with artificial lights, such as fluorescent UV or Xenon Arc light, over a period of time.

As shown in Figs. 8(a) and 8(b), the maximum surface temperatures of white TPO membranes aged in fluorescent UV, concentrated sunlight, and UAWS, match those of white TPO exposed in the 12.7 mm gap area between two solar modules in field exposure in Gainesville, TX.

**Accelerated Weathering Study with a Xenon Arc Apparatus**—Per D6878, the air chamber temperature of the Xenon Arc apparatus was set at 50 °C. Table 5 lists Xenon Arc test results for white TPO membranes. Not surprisingly, all the commercial white TPO membranes pass the minimum UV radiance requirement per D6878, which is 10,080 kJ/m² at 340 nm. Due to the lower temperature that TPO membrane samples experience in the Xenon Arc apparatus it is an accelerated test only useful for predicting weathering performance of TPO membrane not burdened with flexible solar modules, such as at the area 0.914 ms away from the flexible solar module system setup in Fig. 1, where the maximum surface temperature of white TPO membrane is around 54 °C only.

**Accelerated Weathering Study with Fluorescent UV Light only or Followed by Heat Aging**—By referring to ASTM G154, the fluorescent UV test method was modified. The highest irradiance level, 1.55 w/m², and the highest black panel temperature/air chamber temperature, 80 °C, were used to accelerate TPO aging through the combination effect of UV and heat. With UVA-340 lamps, 1.55 w/m² irradiance is more than 2X the UV level of noon summer sunlight and 4.4X the UV level of winter sunlight.

Two variations of this modified method test was performed on white TPO membrane samples to examine weathering performance. In the first, white TPO membrane samples were exposed in the apparatus until the samples show cap cracking under 7X magnification. The second variation involved exposure of white TPO samples in the apparatus for a certain period of time, such as over 2500 hrs or 5800 hrs. Then these samples were put into a 138 °C oven for further heat aging until the samples showed micro-cracking under 7X magnification. The latter variation provides an empirical indication of the level of UV stabilizers/antioxidants left in TPO membrane after UV exposure. Table 6 shows the number of days taken to have micro-cracking of samples for each type of fluorescent UV related test. Based on the days to micro-cracking on the cap side of membranes, the correlation between the two types of fluorescent UV-related tests was derived in Fig. 9. With the correlation model, the days to micro-cracking on the cap side of TPO membrane was predicted for the first type of test.

Regardless of two different UV exposure levels, there is a strong linear correlation between 138 °C heat aging test and the combination of UV followed with 138 °C heat aging test, shown in Fig. 10.

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**TABLE 5—Xenon arc apparatus test results of white TPO membrane samples.**

<table>
<thead>
<tr>
<th>TPO Membrane Samples (Thickness)</th>
<th>UV Exposure (kJ/(m².nm) at 340 nm)</th>
<th>7X Micro-Cracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>F, 2.03 mm</td>
<td>&gt;10,080 kJ/m²</td>
<td>No</td>
</tr>
<tr>
<td>H, 2.03 mm</td>
<td>&gt;20,160 kJ/m²</td>
<td>No</td>
</tr>
<tr>
<td>I, 1.52 mm</td>
<td>&gt;20,160 kJ/m²</td>
<td>No</td>
</tr>
<tr>
<td>J, 2.03 mm</td>
<td>&gt;20,160 kJ/m²</td>
<td>No</td>
</tr>
<tr>
<td>K, 1.52 mm</td>
<td>&gt;20,160 kJ/m²</td>
<td>No</td>
</tr>
<tr>
<td>L, 1.52 mm</td>
<td>&gt;30,240 kJ/m²</td>
<td>No</td>
</tr>
<tr>
<td>M, 2.03 mm</td>
<td>&gt;30,240 kJ/m²</td>
<td>No</td>
</tr>
</tbody>
</table>
plotting the data listed in Table 6 in terms of predicted days to cap cracking with UV exposure versus days to cap cracking in 138 °C oven aging. Fig. 11 shows a strong correlation. It seems that the better heat resistance, the better the UV resistance of TPO membrane, within the ranges measured here.

**Accelerated Outdoor Weathering Study Using Concentrated Natural Sunlight**—In this study, concentrated natural sunlight was used to verify accelerated weathering lab tests, such as fluorescent UV and 138 °C oven heat aging (Table 7). It seems that the concentrated sunlight exposure correlates with the laboratory UV test to some extent.

**Ultra Accelerated Outdoor Weathering Study (UAWS)**—The UAWS was also used to verify accelerated weathering laboratory tests, and 138 °C oven heat aging (Table 8). The maximum surface temperature of exposed TPO samples in the UAWS was monitored over time, with Fig. 8(a), 8(b) and Fig. 12 showing that high heat and high UV dosage were applied to TPO samples exposed on UAWS and the fluorescent UV apparatus. It seems that good correlation among UAWS, fluorescent UV apparatus test, and 138 °C

![Graph showing correlation between UV exposure and days to cap cracking in 138°C oven aging.](image)

**FIG. 9—Correlation of two types of fluorescent UV tests: UV only versus UV first/138 °C oven aging second.**
TABLE 7—Concentrated sunlight vs. fluorescent UV and 138 °C Oven heat aging.

<table>
<thead>
<tr>
<th>Samples (Thickness)</th>
<th>Concentrated Sunlight - AZ</th>
<th>Fluorescent UV</th>
<th>138 °C Oven Heat Aging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TUV to Cap Cracking MJ/m²</td>
<td>Yrs Equal to S.FL Exposure Years</td>
<td>TUV to Cap Cracking MJ/m²</td>
</tr>
<tr>
<td>A, 1.14 mm</td>
<td>~4260</td>
<td>~15</td>
<td>3623</td>
</tr>
<tr>
<td>B, 1.14 mm</td>
<td>~4260</td>
<td>~15</td>
<td>4385</td>
</tr>
<tr>
<td>O, 1.14 mm</td>
<td>~4260</td>
<td>~15</td>
<td>4553</td>
</tr>
</tbody>
</table>

Note: TUV: Total Ultraviolet Radiation is measured between at 295 nm – 385 nm.

TABLE 8—UAWS versus fluorescent UV test and 138 °C oven heat aging.

<table>
<thead>
<tr>
<th>Samples (Thickness)</th>
<th>UAWS - AZ</th>
<th>Fluorescent UV</th>
<th>138 °C Oven Heat Aging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TUV to Cap Cracking MJ/m²</td>
<td>Yrs Equal to S.FL Exposure Years</td>
<td>TUV to Cap Cracking MJ/m²</td>
</tr>
<tr>
<td>P, 1.14 mm</td>
<td>1259</td>
<td>5</td>
<td>1952</td>
</tr>
<tr>
<td>Q, 2.03 mm</td>
<td>10511</td>
<td>38</td>
<td>12770</td>
</tr>
<tr>
<td>R, 2.03 mm</td>
<td>17846</td>
<td>64</td>
<td>18646 (predicted from Fig. 11)</td>
</tr>
</tbody>
</table>

Note: TUV: Total Ultraviolet Radiation is measured between at 295 nm – 385 nm.
oven heat aging can be derived. It again suggests that the higher the heat resistance, the better the weathering resistance of TPO membrane.

Conclusions

1. In this examination of the weathering properties of 13 TPO membranes, representing all of the manufacturers with a commercially available product, the ASTM D6878 test requirement for accelerated weathering, using xenon arc apparatus, was generally met. In the few cases where the requirement was not met, it was by a small amount. Since the study represents a “snapshot” of commercially available membranes, these cases were not deemed to be significant.

2. Heat aging shows large differences between TPO membranes in terms of the onset of surface microcracking. Heat is now known to be causing some early aging of TPO membranes in the field. Studies of membranes overburdened with flexible solar panels show that the TPO adjacent to and underneath these panels can reach temperatures far in excess of previously anticipated service temperatures. In fact, many commercially available membranes cannot be expected to survive for long periods of time with such overburden.

3. Those samples that performed well in heat aging also did well in UV testing and tests using an outdoor accelerated aging system (UAWS). This strongly suggests that membranes designed to survive for long times at high temperatures, such as 138 °C, have excellent UV stability. However, that may only hold for the types of stabilizers used in the membranes studied here.

4. In order to predict the relative life expectancy of TPO membranes under all conditions, it is important to incorporate heat aging as a requirement in any TPO membrane standard. The UAWS and fluorescent UV tests described in this paper seem to be better methods for understanding long-term weathering performance of TPO membrane under high heat conditions, such as TPO membranes installed with a flexible solar module system.

5. The heat aging tests at 116 °C and 138 °C show a strong linear correlation. This suggests that across that range, degradation mechanisms are essentially the same.

References


[11] Trade names or company products are mentioned to specify adequately the materials and test equipment and apparatuses used in the study. In no case does identification imply recommendation or endorsement, nor does it imply that the equipment and apparatuses are the best available for the purpose.


