THERMOPLASTIC POLYOLEFIN (TPO) ROOFING MEMBRANES: THE NORTH AMERICAN EXPERIENCE

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KEYWORDS

Roofing membrane, single-ply roofing, thermoplastic olefin, thermoplastic polyolefin, TPO, polyethylene, polypropylene, flexible polyolefin, FPO, flexible polyolefin alloy, FPA, FPO-A, glass-transition temperature, Tg, dynamic mechanical analysis, DMA, thermal analysis, thermogravimetry, wind resistance, static testing, dynamic testing, failure mode.

ABSTRACT

Over the last 10 years a "new-generation" of single-ply systems have entered the North American market. Most have touted the benefits/properties of being EPDM-like with the weldability of "plastic" membranes. Today, they are generally grouped as a family called thermoplastic polyolefin. This group is a member of the thermoplastic family. Thermoplastics include a wider variety of systems such as, poly[vinyl chloride], (PVC); ketone ethylene ester (KEE), thermoplastic elastomers (TPE), thermoplastic polyolefin (TPO), etc. All thermoplastics share some of the same characteristics, e.g., heat-weldability. However, they have very different chemical and physical/mechanical properties. As part of a five-year investigation, mechanical (strength and elongation) and chemical thermogravimetry and dynamic mechanical analysis methods of evaluation are being used in this paper to characterize in-service thermoplastic polyolefin (TPO) roof membranes. It was found that the polyester scrim reinforced membranes were superior in tensile strength and elongation as compared to those reinforced with random mat of short glass fibres. It was also found that the term TPO could be confusing and very vague because of the multitude of acronyms. Standards should consider differentiating between the different types of TPOs (i.e., polyethylene or polypropylene). Based on thermogravimetry, at least four different formula types of TPOs are currently in service. Also, standards should consider using the glass transition temperature to characterize ageing/weathering of membranes. One of the concerns with TPOs in North America is the field welding of seams. For example, it was reported that cold welds frequently occur; that the start and stop positions of the robotic welder are especially critical, that there is a narrow welding window between cold welds and scorch/burn-through, etc. It was also reported that TPOs could be welded at a faster speed than other thermoplastic membranes. As a result, the effects of welding parameters on the seam strength of TPO roofing membranes were investigated. This paper will report on the above and how it applies to TPOs in North America. It includes a table of physical properties for North American TPOs currently available. Data from recent static and dynamic wind uplift are also presented.

RÉSUMÉ

Au cours des dix dernières années, on a vu apparaître sur le marché nord-américain une « nouvelle génération » de systèmes monocouches dont la plupart ont été présentés comme possédant les avantages et les propriétés de l'EPDM, ainsi que la soudabilité des revêtements « plastiques ». Aujourd'hui, ces systèmes sont regroupés dans une grande famille dite « des thermoplastiques », qui comprend par exemple le poly(chlorure de vinyle) (PVC), le cétone-éthylène-ester (KEE), les élastomères thermoplastiques (TPE), le polyoléfine thermoplastique (TPO). Tous les thermoplastiques partagent certaines caractéristiques, par exemple la thermosoudabilité. Toutefois, ils possèdent des propriétés chimiques, physiques et mécaniques fort différentes. Nous décrivons dans ce document les méthodes d'évaluation mécaniques (résistance et allongement) et chimiques (analyse thermogravimétrique et analyse mécanique dynamique) qui sont utilisées, dans le cadre d'une étude de cinq ans, pour

caractériser les revêtements d'étanchéité en polyoléfine thermoplastique (TPO) qui sont en service. Nous avons constaté que les revêtements à armature polyester possédaient une résistance à la traction et un allongement supérieurs à ceux des revêtements munis d'une armature faite de courtes fibres de verre orientées de façon aléatoire. Nous avons aussi constaté que le sigle TPO pouvait être très vague et constituer une source de confusion. Les normes devraient permettre de distinguer les différents types de TPO. Si l'on se base sur la thermogravimétrie, on emploie actuellement au moins quatre types de formulation de TPO. Les normes devraient aussi utiliser la détermination de la température de transition vitreuse pour caractériser le vieillissement ou l'altération des membranes sous l'effet des conditions extérieures. Le soudage sur le terrain des revêtements constitue l'un des points qui suscitent de l'inquiétude, en Amérique du Nord, en ce qui concerne le TPO. Par exemple, on a signalé la fréquence des soudures faibles, l'aspect crucial des positions de départ et d'arrêt des soudeuses robotisées, ainsi que l'étroitesse de la fenêtre de soudage « soudure faible – brûlure légère ou complète ». Il a aussi été signalé que le soudage des membranes en TPO pouvait être réalisé à une plus grande vitesse que le soudage des revêtements faits d'un autre matériau thermoplastique. C'est pourquoi les effets des paramètres de soudage sur la résistance des joints des revêtements d'étanchéité ont été examinés. Ce rapport fera état des résultats obtenus à ce propos et indiquera comment ils s'appliquent au TPO, en Amérique du Nord. Il comportera un tableau des propriétés physiques des TPO que l'on trouve actuellement sur le marché nord-américain.

ZUSAMMENFASSUNG:

Vor zehn Jahren wurde eine „neue Generation" von einlagigen Dachbeschichtungen auf dem nordamerikanischen Markt eingeführt. Die meisten dieser Produkte verdanken ihren Erfolg der Tatsache, dass sie einerseits die Vorteile/Eigenschaften von EPDMs aufweisen und andererseits wie Kunststoffe schweißfähig sind. Heutzutage werden diese Materialien gewöhnlich unter dem Oberbegriff Thermoplaste zusammengefasst. Zur Gruppe der Thermoplaste gehört eine Vielzahl von Stoffen, u.a. Polyvinylchlorid (PVC), Ketonethylenester (KEE), thermoplastische Elastomere (TPE)

monostrato. Sono stati vantati i benefici/proprietà di saldabilità delle membrane di "plastica" che le apparentano alle EPDM. Queste membrane vengono oggi raggruppate per lo più in una famiglia denominata "termoplastica". Le materie termoplastiche comprendono un'ampia gamma di sistemi come il cloruro di polivinile (PVC), il chetone etilene estere (KEE), gli elastomeri termoplastici (TPE), la poliolefina termoplastica (TPO) ed altri ancora. Le materie termoplastiche sono accomunate da alcune caratteristiche come la termosaldabilità, ma posseggono differenti proprietà chimiche e fisiche/meccaniche. Nel contesto di una ricerca quinquennale, il presente articolo utilizza metodi di misurazione meccanici (resistenza ed allungamento) e chimici (termogravimetria e analisi meccanica dinamica) per illustrare le caratteristiche delle membrane di copertura in poliolefina termoplastica (TPO) attualmente in uso. È stato appurato che le membrane armate di tessuto poliestere presentavano resistenza alla trazione e all'allungamento superiore rispetto a quelle rinforzate da un reticolo randomizzato di fibre di vetro corte. È risultato anche che il termine TPO può generare confusione e risultare vago in America del nord. Le norme accettate dovrebbero considerare una diversificazione tra i differenti tipi di TPO. Con criteri di termogravimetria possiamo distinguere almeno quattro diversi tipi di TPO utilizzati al momento attuale. Inoltre le norme accettate dovrebbero considerare l'utilizzazione della temperatura di transizione vetrosa per definire le caratteristiche di invecchia-mento/degrado da agenti atmosferici delle membrane. Una delle preoccupazioni riguardo le TPO in America del nord riguarda la saldatura delle giunzioni sul campo. È stato riferito, ad esempio, che spesso viene praticata la saldatura a freddo; che la posizione iniziale e finale della saldatrice robotizzata è di cruciale importanza, che il margine tra saldatura a freddo e bruciatura parziale e completa è molto ristretto. È stato anche riferito che i tempi di saldatura delle membrane TPO sono molto più veloci rispetto ad altre membrane termoplastiche. Di conseguenza sono stati studiati gli effetti dei parametri di saldatura sulla resistenza delle giunzioni delle membrane di copertura TPO. L'articolo riferirà sulle problematiche indicate sopra e sulla loro applicazione alle TPO in America del nord. Verrà anche incluso un tabulato delle proprietà fisiche delle TPO nordamericane attualmente disponibili.

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INTRODUCTION

Thermoplastic or flexible polyolefin (TPO or FPO) roof membranes have been in service in Europe and North America for approximately 10 years and the use of this family of membranes in North America is increasing. The focus of this paper will be TPO products available in North America. At first, only a couple manufacturers produced a hand-full of products. Within the last few years, other manufacturers have come on-line with new product offerings. As is expected with any new material entering the market, there has been a learning curve associated with the installation and maintenance of TPOs. The objective of this study is to investigate the long-term performance of in-service thermoplastic polyolefin (TPO) roofing membranes. A range of TPO membranes with different reinforcements, weave styles and polymers is covered.

Definition of TPO

Defining "thermoplastic polyolefin" is difficult. "Thermoplastic" is a generic term in polymer science; it encompasses a class of polymers that soften when heated in a reversible process. The term "olefin" is generic, being an old chemical name for any molecule containing carbon-carbon double bonds (also known as alkenes). Any polymer chain formed by chemically linking up many olefin molecules is termed a polyolefin. These polyolefins only contain carbon and hydrogen atoms. While TPO roofing membranes are relatively "new" (appearing in the last 10 years or so), the polymer technology has been around for some time. Today, polyolefins are used extensively in the automotive industry, plastic bags, bottles, etc. The polymer for TPO roof membranes is reported, from one source, to be an alloy (i.e., a blend) of ethylene and propylene (two monomers that are joined to create a uniform polymer during synthesis).

As can be seen in Figure 1, there are essentially two families of polymer-based roofing membranes: thermosets (TS) and thermoplastics (TP). A polymer is a long-chain molecule consisting of many (poly) small repeating units (mer) ($\sim 10^3$ - 10^6) joined end to end. These molecules are tangled in a random manner analogous to cooked spaghetti. Polymers can be classified into thermoplastics (TPs) and thermosets (TSs) depending on their mechanical behaviour on heating and cooling (see Fig. 1). TPs comprise long-chain molecules held together by weak bonds. When heat is applied, the molecules "slide past" one another and the polymer softens. On cooling, the molecules cannot slide past each other easily and the polymer hardens. TS long-chain molecules, however, are linked together by small molecules via strong chemical bonds, a process sometimes referred to as vulcanization (cross-linking). This three-dimensional network is so rigid that the molecules cannot move very much even when the polymer is heated. Thus, TSs do not soften when heated. Because of these differences, TP and TS membrane sheets are bonded differently when applied. TPs can be bonded using heat welding; the hot air melts the polymer at the seam and the two strips of membranes become fused. TS membranes are usually bonded using adhesives or tapes. Thermoplastics soften when heated and harden on cooling (the softening/hardening cycle may be re-occur often) but thermosets do not. Thermosets include the commonly used ethylene propylene diene monomer [also known as ethylene propylene diene terpolymer] (EPDM), while thermoplastics encompass a wider variety of roofing membranes (e.g., PVC, EVA), including thermoplastic polyolefins (TPOs).

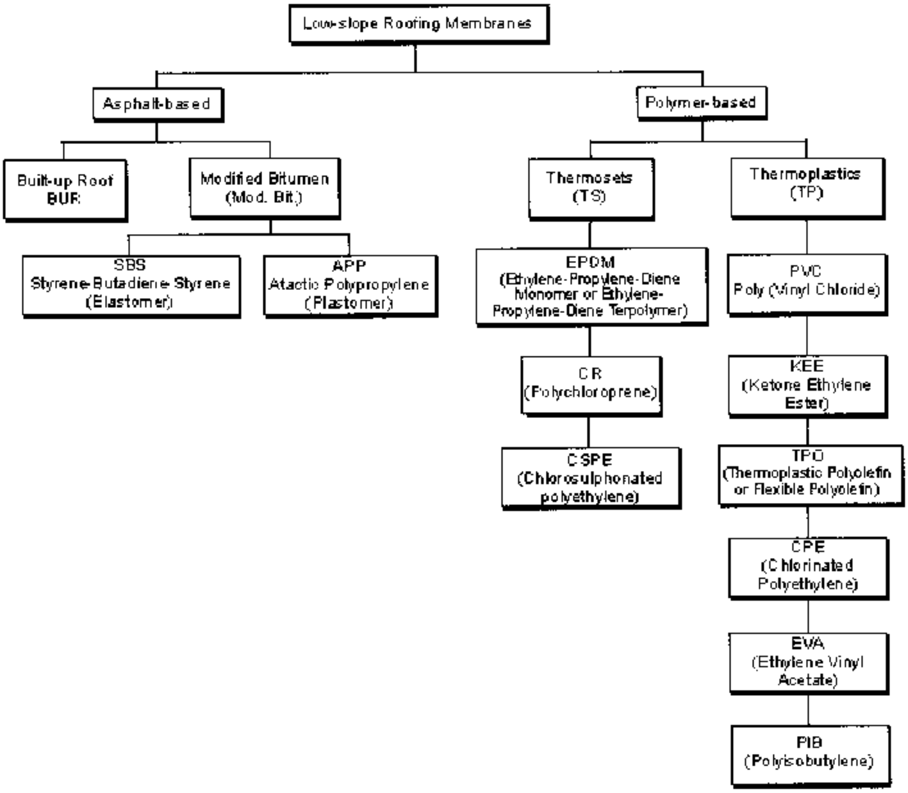


Figure 1

All thermoplastic roofing membranes share certain characteristics, e.g., heat welding can be used for seaming. However, for the most part they have very different chemical, physical and mechanical properties. It is impossible to explain these differences here but there are different ASTM material-based standards for various TP products. To avoid confusion, one should not just label all of these products simply as TP products. TPOs differ from other TPs in several aspects, and thus they must be handled and applied differently.

According to the latest draft ASTM standard for TPO roofing membranes, the composition is very non-specific. The polymer itself is not defined within the standard, which states only that the sheet shall contain the "appropriate" polymers. Because of this loose definition, there is an endless list of chemicals that would fall under this standard (e.g., ethylene, propylene, and isobutylene, as well as their derivatives). Ideally, manufacturers should specify the exact polymer in terms of marketing and labelling. Table 1, lists the ASTM proposed physical requirements for a TPO sheet.

There are a few published papers that attempt to explain the different types of TPOs [1-4]. One point is clear, however: unlike plasticized thermoplastic membranes, TPOs do not contain plasticizers (small molecules added during compounding to increase the flexibility of the product). Therefore, the problem of plasticizer loss associated with some TP membranes is eliminated for TPO membranes.

Confusion in the Market Place

The confusion associated with TPOs comes from both the chemical terminology and the product marketing. Product marketing has promoted mainly the EPDM-like characteristics of TPOs, i.e., it being like rubber with the added benefits of welded seams (which EPDMs do not have). Also promoted has been the chemical resistance attributed to the polypropylene component of the polymers. The confusion also lies in the fact that there are on the market products called thermoplastic polyolefin rubber or thermoplastic polyolefin elastomer (propylene bended with ethylene-propylene rubber) whose acronym is TPO. Moreover, some confusion has occurred, regarding the use of the term thermoplastic (TP). It is important to remember that all TPOs are thermoplastic (i.e., TPs) but only some TPs are TPOs (see Fig. 1).

Benefits of TPOs

In general, TPO membranes are being marketed as a product that combines the properties of EPDM and PVC without the associated drawbacks that the latter two materials have. In other words, they are supposed to be as UV-resistant and as heat-resistant as EPDM, and as heat-weldable as PVC.

The following benefits and characteristics have been reported for TPOs [1-3]:

- environmentally friendly and recyclable
- seams can be heat welded
- available in many colours
- resistant to heat, UV degradation
- resistant to many chemicals
- good cold-temperature flexibility
- no plasticizers added
- contains no chlorine

North American Products

At the present time, eight North American membrane manufacturers are known to market TPO roofing membranes. The eight manufacturers were requested to furnish prescribed baseline information. The following summarizes the information submitted by the eight manufacturers:

- Year of first commercial use in North America: 1990, 1992 (two manufacturers), 1993, 1994, 1995, 1999, and 2000.
- Distribution outside of North America: Four of the manufacturers distribute their TPO in other countries in Asia, South America, and Europe.
- Seven of the manufacturer's TPOs are manufactured in the U.S. One of these manufacturers also produces the product under license in Japan and Norway. One manufacturer's product is produced in Europe.
- Five of the manufacturers produce their TPO. Three of the manufacturers market TPO produced by another manufacturer.
- The field sheets produced by all eight manufacturers are reinforced.
- For the flashing sheets, three manufacturers produce a non-reinforced product, two produce a reinforced product, and three produce both reinforced and non-reinforced products.
- *Attachment methods*: Four manufacturers offer ballasted, fully adhered, mechanically attached, and protected membrane (PMR) systems. Two manufacturers offer ballasted, fully adhered, and mechanically attached. One manufacturer offers fully adhered and mechanically attached. One manufacturer offers ballasted and PMR.

- *Field seaming method*: All eight manufacturers specify heat welding.
- *Sealant at edge of field seams:* Two manufacturers require edge sealing, and one requires it only at cut edges. Four manufacturers do not require edge sealing, and one manufacturer does not require it in most cases.
- *Standard thickness*: Seven manufacturers supply 1.1 mm (0.045") and 1.5 mm (0.060") thick sheets. One manufacturer supplies 1.2 mm (0.048") and 1.8 mm (0.072").

TABLE 1- ASTM Proposed Physical Requirements for TPO Sheet

	Type I
Thickness, min, mm (in.)	
Sheet-overall	1.0 (0.039)
Coating over scrim	0.225(0.009)
Breaking strength, min, kN (lbf)	0.75 (169)
Elongation at break, min, %	13[A]
Tearing strength, min, N (lbf)	156 (35)
Brittleness point, max, °C (°F)	-45 (-53)
Ozone resistance, no cracks	Pass
Properties after heat aging: (retained values)	
Breaking strength, % min	90
Elongation at break, % min	90[A]
Tearing strength, % min 60	
Weight Change (Mass), max %	±4[B]
Linear dimensional change, max, %	±2.00
Water absorption, max, mass %	±3.0[B]
Factory seam strength, min, kN (lbf.)	0.29 (66)
Weather resistance:	
Visual inspection	Pass
Breaking strength, % min	90
Elongation at break, min, %	90[A]

[A] for reinforcing fabric only.

[B] Test performed on top coating material only. (Use D-471, Testing only one side Section)

Physical Properties: In the absence of an ASTM product standard, it is difficult to compare physical properties of the different membranes because the manufacturers use different test methods and test conditions (many of which were not specified). In addition, some of the values are reported as minimums, while others are reported as being typical. While the manufacturers provided data on most of the properties in the proposed ASTM standard (Table 1), values were not reported on all of the properties. The following table provides a synopsis of reported values:

- Breaking strength, min, kN (lbf): ASTM D 751, values range from 0.89 (200) to 1.38 (310).
- Elongation at break, min. %: ASTM D 751 and D 412, values ranged from 25 to 30% (500% for the product tested in accordance with D 412).
- Tearing strength, min. N (lbf): ASTM D 751 and D 624, values ranged from 245 (55) to 445 (100).
- Brittleness point, max. °C (°F): ASTM D 2137, values ranged from -40 (-40) to -51 (-60).
- Ozone resistance, no cracks: ASTM D 1149.
- Properties after heat aging: (retained values)
  - Breaking strength, % min.: Some manufacturers reported a percentage of retained value (which varied from 90 to 95%), while others reported the actual breaking strength.
  - Elongation at break, % min.: Values ranged from 90 to 95% of the unconditioned specimens. However, one manufacturer reported the actual elongation (30%).
  - Tearing strength, % min.: Some manufacturers reported a percentage of retained value (95% in one case), while others reported the actual tearing strength.
  - Weight change (Mass), max. %: only one manufacturer reported this value.
- Linear dimensional change, max. %: ASTM D 1204, values were similar, with a ± 1% maximum range.
- Water absorption, max., mass %: ASTM D 471, values were similar, with a ± 4% maximum range.
- Factory seam strength, min. kN (lbf): ASTM D 638, D 751, and D 1876. In some cases, field seam strength was reported and in some cases it was not clear if the reported value was for a field or factory seam.
- Weather resistance: The manufacturers used a variety of test methods and exposure times. Visual inspection for cracking was reported. However, breaking strength and elongation at

break after exposure (which are included in the proposed ASTM product standard) were not reported.

A few manufacturers reported on other properties that are not in the proposed ASTM product standard, including hydrostatic resistance, puncture resistance (using FTM 101B or FTM 101 C), solar reflectance, and water vapor permeance.

Performance of TPOs

TPO membranes are lighter in weight and easier to handle than the other thermoplastic membranes. But, while flexible, they have a rather rigid feel: they tend to hold their shape, and do not relax quickly. Contractors appear to be adjusting slowly to them; some say they are not "contractor-friendly" while others like working with them. Their comments include the following:

- Hot-air-welded seams are easier and cleaner than adhesive-based seams;
- Material is not as heavy (i.e. roll weight) so it is easier to handle;
- Lower cost than other hot-air-welded membranes;
- Mechanically fastened systems (as opposed to loose laid or fully adhered systems) work well in re-cover applications without adding extra load;
- Non-reinforced flashing membranes easy to form for detailing;
- Stiff field membrane that does not relax well;
- Noticeable changes in colour (e.g., yellowing) and texture over time (i.e., after solar exposure);
- Membranes respond dramatically (expansion and contraction) to temperature changes (this could be related to installation issues);
- Cold welds (i.e., welds at temperatures that are not hot enough) frequently occur with some membranes; the start and stop positions of the robotic welder are especially critical, as are the positions of T-joints;
- Narrow welding window between cold welds and scorch/burn-through (i.e., welds at temperatures that are too hot);
- Occasional failure of substrate bonding adhesive (i.e., not sticking to membrane);
- Re-welding membranes (in repair) problematic after

exposure to sun;

- Black membranes are hot to the touch after exposure to the sun;
- Membrane edge caulk can be runny on a hot day;
- Black membranes more difficult to weld than white;
- Cigarettes burn holes in the membrane more easily than for other thermoplastic membranes.

Current Research Results

TPO roofing membranes have been in service in Europe and North America for approximately ten years. The first appearance of a "TPO-type" roofing product in the United States was around 1987. As yet, little is known about their durability.

Evaluation of In-service TPO Roofing Membranes [5]
NRC/IRC, Building Envelope and Structure Performance, in collaboration with Benchmark Inc., a roofing consulting firm, initiated a five-year project in 1997 to study the long-term performance of TPO membranes.

Thus far it has been found that the membranes reinforced with continuous polyester fibre scrim had significantly higher tensile breaking strength than those reinforced with random short glass fibre mat. With the polyester scrim (continuous fibre bundles arranged in a grid), the fibres bore the majority of the applied stress until failure, resulting in high breaking strength. In the case of the glass fibre mat reinforcement (chopped fibre strands packed randomly into a mat), the fibre strands flowed and aligned themselves with the polymer in the direction of the applied stress, resulting in significantly lower breaking strength — i.e., the strands moved with the membrane rather than stretching and eventually snapping as in the case of the polyester.

The breaking strength of the polyester scrim membranes was governed by the number of fibre tows (bundles or end-counts) across the width of the specimen. The strength of the fibre tows was the same for all samples, independent of the surface coating. Therefore, the tighter the weave of the reinforcement the higher the breaking strength of the membrane. This can also be achieved by increasing the weight of the reinforcement.

For the test method used, the difference in weave style also had an effect on how the membrane failed. One sample was reinforced with an uncoated polyester scrim where fine, continuous polyester fibres held the intersecting tows together. When the membrane was pulled in the machine direction (parallel to the length of the roll of the membrane), the fine fibres stretched and tightly held onto the tows in the cross direction (perpendicular to the machine direction), creating high localized stresses at the intersections. However, when the membrane was stressed in the cross direction, no localized stress points were formed since the fine fibres held the tows in the machine direction by sandwiching instead of pulling them.

The breaking strength of the polyester scrim membranes increased by 20–30% as the test temperature dropped to -40°C. However, the membrane became brittle and the ultimate elongation (a measure of the membrane's ability to accommodate deck movement) reduced more than 15 times. Since the flexibility of the polymer governs that of the membrane, it is recommended that polymers with superior cold-temperature mechanical properties (e.g., higher elongation) be used in membranes intended for cold temperature applications. The glass transition temperature (T_g) is a good criterion for choosing the right polymer.

Glass Transition Temperature (T_g) - When a polymer is warm, the molecular segments are constantly changing place by actively sliding or jumping and the polymer is flexible. This is the amorphous state. When the polymer is cooled, molecular movement starts to slowdown. If cooling is continued, a temperature will be reached at which molecular movement stops altogether. The polymer loses its flexibility and becomes brittle. This is the glassy state. The temperature at which the transition from flexible to brittle occurs is called the glass transition temperature (T_g). T_g is a property of the polymer and is an important concept in evaluating the performance of polymer-based roofing membranes. The addition of plasticizers (small polymer molecules) during compounding helps to lower the T_g by increasing the distance between the polymer molecules and thereby softening the polymer. TPO's do not have added plasticizers. A TPO's flexibility is an inherent property of the polymer. TPO's have similar T_g compared to other single-ply membranes.

Cold temperature flexibility was monitored using T_g. The T_g for the unaged membranes was found to be in the range of -32°C to -37°C, comparable to that of other thermoplastic single-ply systems (around -35°C). There was one exception — a T_g of -54°C. That sample also had the highest tensile elongation at -40°C.

Thermogravimetry (which monitors the weight change of a subject sample being heated over a temperature range) clearly showed there are at least four different formula types of TPOs (among four manufacturers sampled) based on weight loss patterns alone. This shows again that the term TPO is quite generic, encompassing many different types of polymers.

Effects of Welding Parameters on Seam Strength of Thermoplastic Polyolefin (TPO) Roofing Membranes [6]

NRC/IRC, Building Envelope and Structure Performance, with the assistance of Dryspace, Inc., a roofing contractor, studied how the parameters of robotic welder affected the seam strength of speed and temperature comparing five TPO membranes (obtained from distributor's stock) and the seam strength attained.

The speed and temperature of the robotic welder were varied to obtain a wide range of membrane surface temperatures. The quality of the welds was categorised during the welding based on visual inspection, pulling at the seam by hand, and measuring the membrane's surface temperature. A total of 63 combinations were made. Eliminating those trials that produced defective seams in the welding process (e.g. not welded, fell apart or damaged due to scorching), a total of 38 seamed areas were isolated for testing. Seam strength was tested using ASTM D751, utilizing a minimum a three specimens cut across the seam in each area.

Three of the products consistently failed *cohesively* within the sheet being peeled along the reinforcement-polymer interface, with the weld remaining in tact, indicating acceptable welds.

One product exhibited two failure modes depending on the welding conditions. Colder welds failed *adhesively* at the membrane interface, indicating poor welds. Examination of the failure surface revealed that melting only occurred at the top of the ridges of the reinforcement. This possibly explains observations from the field when running the welder too fast or too cold. The resultant seam appears good at first and may probe tight, but these welds have been observed to fail with a few days or weeks after being in-service. The specimens welded at hotter temperatures failed *cohesively* within the sheet being peeled along the reinforcement-polymer interface, with the weld remaining in tact, indicating acceptable welds.

The final product failed adhesively at the interface of the two sheets. The failed surfaces were relatively smooth. Examination of the failure surface showed that the two sheets were held together by fusion. Only at a number of a lines were observed on the membrane surfaces perpendicular to the testing direction, reflected as peaks in force-displacement curve. For some of these specimens, the two sheets were welded very well at the end of the seam and the top sheet stretched a great deal before it finally separated from the bottom sheet.

Overall, the seam strengths ranged from 2.5 to 9 kN/m (14 to 51 lbf/in.). Seam strengths varied greatly among membrane types and welder speed. In general, the seams, which failed cohesively in the polymer, had higher strengths (4.5 to 9.0 kN/m or 26 to 51 lbf/in.) while those that failed adhesively between the two membrane sheets had lower strengths (2.5 to 4.5 kN/m or 14 to 26 lbf/in.). The exception was the final product, which failed adhesively, but attained strengths over 7 kN/m (40 lbf/in.) for some specimens due to the stronger weld at the end of the seams. There currently is no recommendation in the ASTM draft standard for field seam strength. It has not been investigated if this is a performance concern. Insufficient research and data are available at this time to draw any conclusions. Any detriment in performance due to lower seam strengths would be especially problematic for mechanically fastened membrane applications, where stress can be focussed at the seams during uplift conditions.

The ease of welding depends on the melting temperature and the welding window of the TPO membrane. A product with the narrowest welding window and highest melting temperature is the most difficult to weld. It would be beneficial if the manufacturer of the membrane would specify a welding window, which would be membrane and welder dependent. It is not always possible for a technician to accurately determine the optimum welding window in the field.

As for any thermoplastic membrane, acceptable welds can be obtained with proper use of the welding equipment. An experienced technician, familiar with the robotic welding equipment and field conditions, is essential. Of equal importance is quality control measures used by the technician in the field including, probing of completed seams and pulling apart cut-out seam samples from suspect areas.

Performance of TPO systems under Dynamic Wind Uplift [7]

A North American roofing consortium, the ***Special Interest Group for Dynamic Evaluation of Roofing Systems* - *SIGDERS*** (SIGDERS consists of NRC, manufacturers and building owners - Canada Post Corporation, Department of National Defense, Public Works and Government Services Canada; and associations - Canadian Roofing Contractors' Association, National Roofing Contractors' Association, Roofing Consultants Institute, Industrial Risk Insurers) was established at the National Research Council of Canada to develop a test standard for evaluating roofing systems under dynamic conditions. Research efforts by SIGDERS have led to the development of a facility that allows the evaluation of roof systems in a dynamic mode. Furthermore, SIGDERS developed a new dynamic load cycle for the evaluation of roofing systems under a dynamic environment. This section investigates the responses of TPO systems under both static and dynamic uplift conditions. Similar investigations for PVC systems are documented by Baskaran and Lei [7]. It was shown that the static test protocol over-estimated the design parameters (pressure, fastener load, and membrane deflection), and also produced fastener pullout failure modes. The failure modes resulting from the SIGDERS dynamic test protocol, however, mimicked the conditions observed in field evaluations.

Experimental Set Up: All of the experiments were carried out at the Dynamic Roofing Facility (DRF) established at the Institute for Research in Construction at the National Research Council of Canada (NRC-IRC). Three identical TPO roof assemblies were evaluated under the three different test methods (i.e., FM cycle, UEAtc, and SIGDERS). The system details, layout and instrumentation locations were identical for all three specimens. The tested system consisted of all three main roofing components whose general properties are summarized below:

- Steel deck (structural support),
- Polyisocyanurate insulation (thermal insulation), and
- Mechanically fastened reinforced TPO membrane (waterproofing component).

Details of the tested system are depicted in Figure 2. Three full-width sheets were installed, with dummy sheets at either end. The four seams shown in Figure 2 indicate the fastener locations. For the tested system, membrane sheets were fastened at every 305 mm (12 in) apart along the seam. Fasteners were 127 mm (5 in) long with a plastic plate 51 mm (2 in) in diameter. Figure 2 also depicts the details of a typical seam and edge conditions. Each seam had an overlap of 127 mm (5 in), with the fastener placed 38 mm (1.5 in) from the edge of the under sheet, and 89 mm (3.5 in) from the edge of the overlapping sheet. The portion of the seam beyond the fastener row was welded with hot air such that a waterproof top surface was obtained. The width of the welded portion varied between 38 and 45 mm (1.5 and 1.75 in).

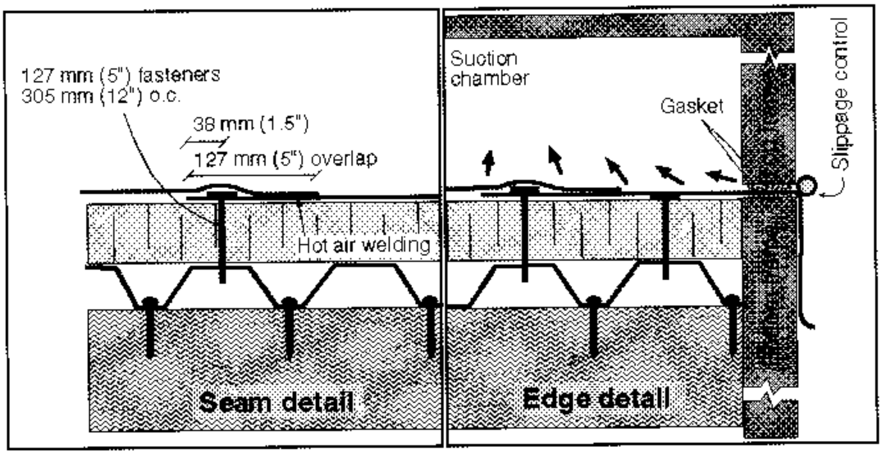


Figure 2: TPO System Layout with seam and edge detail

System Responses: Figure 3 compares the system response between the UEAtc and SIGDERS load cycles. The investigated TPO system passed all 2200 cycles of the SIGDERS protocol. As well, a similar system tested in the UEAtc procedure passed all gusts in 19 cycles (each cycle has 1415 gusts). There are only 16 data points (△) for UEAtc due to the fact that the first, second, third and fourth cycles are applied at the same pressure level. Four points (▲) corresponding to the Group 1 load sequence are shown as SIGDERS data. Group 2 data are not included in this comparison because, as shown in Figure 2, Group 2 pressure cycles are applied over a constant static component to mimic the membrane fluttering effects. However, in the UEAtc process such a feature does not exist. Therefore, the system responses (in this case, deflection data)

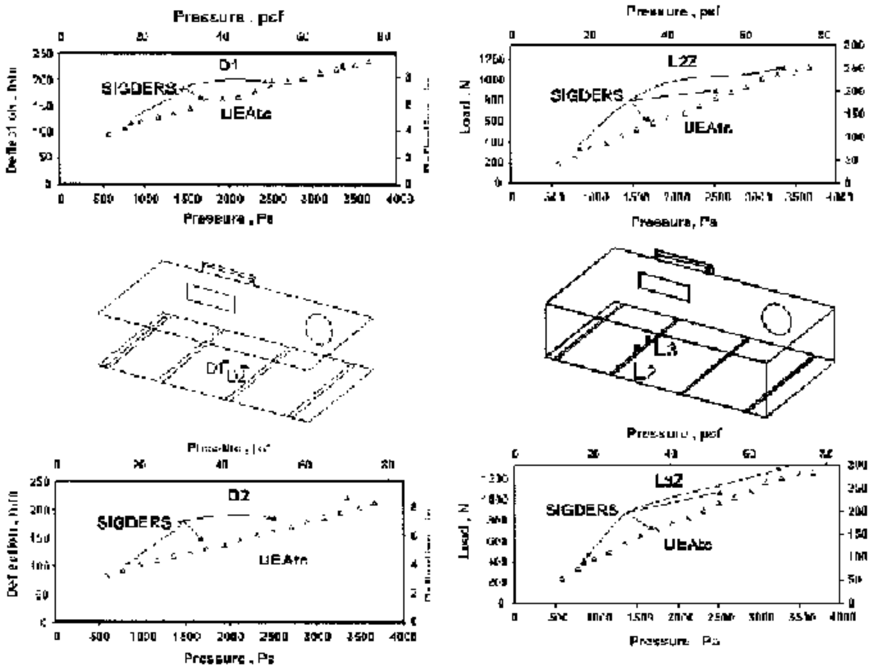


Figure 3 Comparison of the System Response under SIGDERS and UEAtc load cycles.

are compared only for pressure cycles starting from zero. At D1, the deflection data produced by the two load cycles are nearly identical at the same pressure. At D2, however, the deflection produced by the SIGDERS load cycle appears to be nearly 25 mm (1 in) greater than the deflection at the same pressure in the UEAtc load cycle. The greater deflection may be due to a greater dynamic effect of the SIGDERS load cycle, which applies more high-intensity gusts than the UEAtc cycle does. (14% of the gusts applied by SIGDERS are high-intensity, compared to 1% of gusts by UEAtc.)

Fastener loads comparison indicates that the measured fastener loads observed during the two different load cycles compare favorably, although the fastener loads measured under the SIGDERS load cycle were slightly higher than at the same pressure level for the UEAtc load cycle. To quantify the measured fastener force difference between UEAtc and SIGDERS, data pairs were selected. This was done for both locations L2 and L3 as marked on the Figure 2. The mean difference is calculated as follows:

$$\Delta F = \sum_{i=1}^{4} \left\{ \frac{F_{spi} - F_{upi}}{F_{spi}} \right\} x100 \qquad (1)$$

Where:

F_{spi} = Measured fastener forces from SIGDERS load cycle at a given applied pressure.

F_{upi} = Measured fastener forces from UEAtc Load cycle at a given applied pressure.

At L2, the mean difference is about 9%. Similarly, at the membrane central location where the maximum forces are expected the difference is only 8%. A comparison of this nature clearly reveals that the predicted system responses are similar between the UEAtc and SIGDERS load cycles. It is worth mentioning again that not only were the system responses similar between the UEAtc and SIGDERS load cycles, but both procedures also result in similar failure modes as discussed below.

Examination of the system after the test revealed that the membrane had experienced some stretching, and bore teeth marks from the plastic fastener plates, as shown in Figure 4. The stretching around the fastener plates indicates that the system's eventual failure would likely have been in a manner similar to the membrane tear under the UEAtc load cycle. This stretching effect corresponds to field roof failure observations. Kramer [8] states that the most commonly observed failure for mechanically attached single-ply roof membranes is, "*Slippage of roof membrane from below attachment plate leading to loss of compression between roof membrane, insulation substrate, and fastening elements and ultimately to membrane failure by way of tear spread around the fastener shaft*". This observation coincides with SIGDERS failure mode and indicates that the SIGDERS load cycle is inducing wind dynamics on roof systems. The FM static test, however, did not produce this effect on the membrane, and therefore did not reveal the weakest link of the system's wind-uplift resistance.

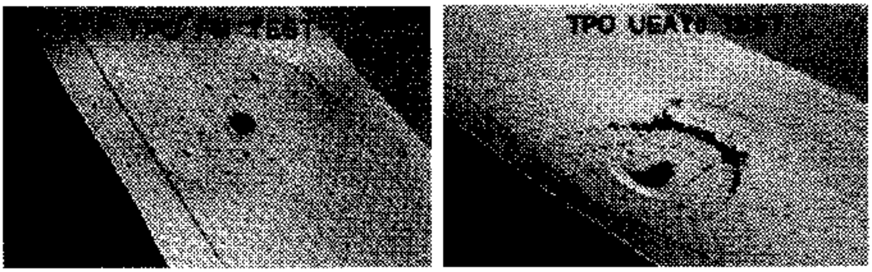
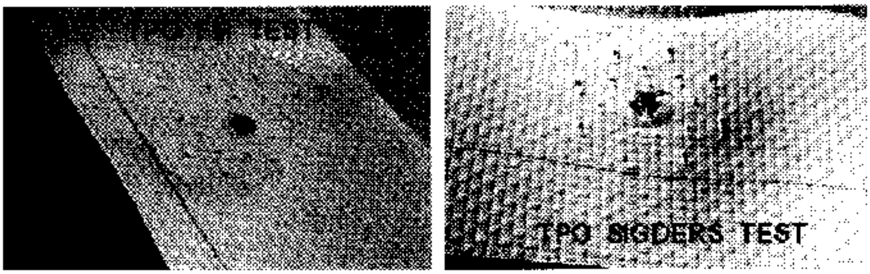


Plate used on the UEAtc membrane had damaged the membrane while the FM test showed no damage due to the plate.



Comparing the tear effect of the plate. Note the teeth marks and also the line in the SIGDERS test had been scratched.

Figure 4: Membrane condition after FM , UEAtc and SIGDERS tests.

Table 2 summarizes the data from all three investigated load cycles. One should exercise caution in comparing the static data with data obtained from dynamic testing. It is important to notice that the system failed, under the FM static loading, due to membrane fasteners pulled out from the deck, under the UEAtc load cycle the system's failure was due to membrane tear around the fastener plates and at the seams. This membrane tear corresponds with failure modes observed in the field [Gerhardt [9], Kramer [10] and Smith [11].

The data presented in Table 2 represent the conditions that the system sustained. In contrast with the difference in the static and dynamic failure modes, only minimal differences are noted in the measured loads. Differences of 241 Pa (5 psf) in the pressure and 15 mm (19/32") in the deflection are observed. It is worth comparing these findings with that of Baskaran and Lei [7] from their similar investigations on reinforced PVC systems. Comparing the design parameters between FM and SIGDERS, they concluded that the FM procedure overestimated the design parameters (pressure by 43% and fastener load by 52%) for the PVC system. Nevertheless, as grouped in Table 2, the differences between FM and SIGDERS are minimal in the case of investigated TPO systems. As indicated before, both PVC and TPO belong to the same family of thermoplastic membranes. However, their formulation and reinforcement layouts are different, which causes the differences in their system responses.

Table 2: Comparison of the design parameters measured from different load cycles for system-sustained scenario

Parameter	UEAtc	SIGDERS	FM
Applied Pressure Pa (psf)	3447 (72)	3350 (70)	3591 (75)
Measured Force N (lbf)	1249 (281)	1333 (300)	1328 (299)
Measured Deflection mm (in)	226 (8.9)	224 (8.8)	209 (8.2)

Summary

Because of the chemical terminology involved, the non-specific chemical composition of the polymer and the marketing focus of manufacturers, there is much confusion about TPO roofing membranes. Manufacturers should consider clearly stating whether their product is a polypropylene- or polyethylene-based system to minimize possible confusion.

Thermogravimetry showed that the formulation of some manufacturers' TPOs has changed over time; sometimes, a rather short time period. Asking for artificial weathering results (see Table 1) and change in glass transition temperatures after weathering (based on guidelines established in the proposed ASTM TPO standard) for "new" products is one factor designers and contractors should consider to gauge potential product performance.

For products with welding "issues", differential scanning calorimetry (DSC) and simultaneous thermal analysis (TG/DTA) can be used to measure the melting point of the product, thereby determining if there is an unusually high melting point or narrow welding window. These tests are advanced laboratory techniques performed by chemists. Manufacturers should provide data on welding windows for each lot of product or at the very least, provide the starting temperature and initial welding speed to the contractor.

The FM test produced a fastener pullout failure mode. The failure modes produced by the SIGDERS and UEAtc dynamic load cycles corresponded with failure modes observed in the field, demonstrating that investigations based on dynamic load cycles have effects that are close to real wind effects on roof systems. Both UEAtc and SIGDERS load cycles are beneficial for evaluating the performance of roof systems under dynamic conditions. Nevertheless, the SIGDERS procedure took 50 hours less time to complete than the UEAtc test.

Thermoplastic polyolefin roof membranes have been in service in Europe and North America for approximately 10 years and the use of this family of membranes in North America is increasing. As is expected with any new material entering the market, there has been a learning curve associated with the installation and maintenance of TPOs. As the use of TPO membranes become more common, it is expected that the familiarity and comfort-level will increase among the users.

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