A PERFORMANCE CLASSIFICATION SYSTEM FOR POLYMER-BASED ROOFING MEMBRANE MATERIALS

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The purpose of this paper is to present a preliminary performance classification system for polymer-based roofing membrane materials. It is hoped that it will encourage discussion and promote work toward an industry consensus standard. Examples of some current membranes and their classifications are included to illustrate the system. The paper does not discuss performance requirements of membrane roof systems.

The scope of this paper is limited to polymer-based roofing membrane materials, but the classification system could be expanded to include modified bitumen materials. Polymer-based membranes include, but are not limited to, chloro-sulfonyl-polyethylene (CSM), ethylene oxide/chloromethyl oxirane (ECO), ethylene-propylene-diene terpolymer (EPDM), polyvinyl chloride (PVC) and PVC blends with other polymers, and thermoplastic olefin elastomer (TPO) formulations. Membrane constructions include nonreinforced, internal reinforcement with fabric or fibers, and fabric backed.

KEYWORDS

Dimensional stability, elongation, flexibility, polymer-based roofing membranes, puncture, ozone resistance, tear strength and weathering resistance.

INTRODUCTION

All polymer-based roofing membranes are subjected to environmental conditions that can alter the physical and chemical properties of the material. These conditions include ozone, heat, solar radiation, thermal cycling, freeze/thaw, pollution, biological growth, and ponded water. Roofing membrane properties must be maintained during exposure to the roof environment, or the roof system will not perform as expected. Material specifications for EPDM, PVC, CSM, and other polymeric roofing membranes are available, but their performance properties are difficult to compare because test methods and conditions are not standardized.

ASTM Standard D 2000[1] is a classification system for rubber products in automotive applications. It allows specifiers and users of automotive rubber compounds to compare and select materials based on standard test methods and conditions. The ASTM D 2000 system also permits a complete description of the quality of these materials.

The purpose of this paper is to promote thought and discussion about a similar classification system for polymeric materials for roofing membranes. A good classification system would help a roof system specifier select an appropriate roofing membrane based on required performance properties developed from test data collected using standard test methods and aging/weathering conditions. The current ASTM test methods and aging conditions will be shown, and where the methods/conditions are different, a proposed standardized test method or condition will be recommended.

DISCUSSION

The ability of a roofing membrane to perform as expected depends on its physical and chemical properties. These properties include tensile/breaking strength, elongation, tear strength, puncture resistance, low-temperature flexibility, and dimensional stability. Although these fundamental performance properties are related, it is best to determine each property individually because of the complex interactions between the properties. An example of this is seen in fabric-reinforced membranes; an increase in breaking strength generally improves puncture resistance. This does not mean, however, that a 25 percent increase in breaking strength will provide a 25 percent increase in puncture resistance.

Membrane Test Methods

Test methods for determining physical properties of the various polymeric sheets are different because of the base polymer used and the sheet construction. Roofing membranes that are based on rubber generally use test methods and conditions established to test rubber articles. ASTM test methods for rubber are under the jurisdiction of ASTM Committee D-11 on Rubber. Test methods for thermoplastic elastomers (includes thermoplastic olefins) are identical to vulcanized rubber in many standards and are also under D-11 jurisdiction.

ASTM test methods for membranes based on plastics (e.g., PVC) are under the jurisdiction of ASTM Committee D-20 on Plastics. Some test methods for rubber and plastic are similar, such as ASTM D 624[1] for rubber tear strength and ASTM D 1004[2] for the tear resistance of plastic film and sheeting. Other methods are very different, and the results cannot be compared.

The complexity does not end with the membrane polymer type. Test methods for nonreinforced products are usually very different from test methods for reinforced roofing membranes. Thoroughly understanding the differences between rubber and plastic test methods and results, as well as sheet construction differences, is a challenge for even the experienced polymer materials technologist. How can we expect a roof materials specifier to determine the best-performing membrane for the building owner?

Fundamental Performance Properties

This section covers most of the important performance properties of a polymer-based roofing membrane. Performance properties are separated from aging and environmental exposure conditions discussed in the next section. To say that a membrane has good resistance to heat aging really means that the membrane's performance properties remain above acceptable levels after the environmental exposure condition of heat aging. Roofing membranes also have properties that are not fundamental performance properties. Specific gravity is an example of a membrane physical property that is not a fundamental performance property except in unusual applications.

Strength—Strength is the force required to rupture the membrane. This includes tensile strength and breaking strength. The main test methods currently in use are ASTM D 412[1] (rubber) and ASTM D 638[2] (plastic) for nonreinforced membranes and ASTM D 751[3] for reinforced membranes. Test results are reported as force per cross-sectional area or force per unit width. Confusion occurs most frequently when the strength of nonreinforced and reinforced membranes are compared.

The recommended method of comparison is ASTM D 2523[4] "Standard Practice for Testing Load-Strain Properties of Roofing Membranes." This method uses a dumbbell test specimen with a 25 mm restricted width and 50 mm pull tabs. The strength (test method load) of the membrane is reported as force per unit specimen width. For example, a 1.5-mm thick nonreinforced sheet with a tensile strength of 11 MPa would have a ASTM D 2523 test strength of 16.5 kN/m. As the thickness of the membrane increases (tensile strength remains constant), the strength also increases. A fabric- or fiber-reinforced membrane with an ASTM D 751 breaking strength of 700 N (ASTM D 751 grip width of 25 mm) would have a strength of about 27.6 kN/m. With this method, the strengths of all roofing membranes are determined using the same test specimen, and the results are reported in the same units.

With strength (S) now reported in standard units of measurement for all membranes, classification values can be established based on performance levels:

- S4: 30 kN/m or higher
- S3: 20.0 to 29.9 kN/m
- S2: 10.0 to 19.9 kN/m
- S1: Less than 10.0 kN/m

Example: A membrane with an average strength of 15.0 kN/m has a strength level of S2.

Elongation—Elongation is the increase in length of a test specimen expressed as a percentage of the original length. Nonreinforced membrane elongation is generally an ultimate elongation, defined as the elongation at which rupture occurs during the application of a uniformly applied tensile stress. Nonreinforced membranes are tested using ASTM D 412 (rubber) or ASTM D 638 (plastic). The elongation (ultimate elongation) of a nonreinforced membrane that has an original specimen length of 50 mm and ruptures at a final length of 100 mm is 100 percent.

Reinforced membranes usually have two elongations: one at the rupture of the reinforcing fabric/fiber and the second when the coating breaks. The reinforcement typically ruptures below an elongation of 40 percent, and the coating over the reinforcement continues to stretch until it ruptures. During the test, the rupture elongation of the reinforcement usually produces the highest force on the stress/strain curve. Elongation failure of a reinforced membrane is the point at which the fabric/fiber ruptures though the coating may still provide for a watertight roof. Reinforced membrane elongation is determined by ASTM D 751.

Although high elongation may be desirable for some roof systems, low elongation and high strength are better for other roof systems. Mechanically attached roof systems generally use reinforced membranes with high strength and low elongation. The recommended test method for elongation is ASTM D 2523, which is also used to determine membrane strength. Elongation (E) is a fundamental performance property with levels established for ultimate elongation (nonreinforced membranes) and for fabric rupture elongation (reinforced membranes):

- E4: 200 percent or higher
- E3: 150 to 199 percent
- E2: 50 to 149 percent
- E1: Less than 50 percent

Example: A nonreinforced membrane with an average ultimate elongation of 300 percent has an elongation level of E4. A reinforced membrane with an average fabric rupture elongation of 35 percent is level E1.

Tear Strength—Roofing membranes may fail in roofing applications because of a special type of rupture called a tear. ASTM D 624 defines tear strength as the force per unit thickness to (1) initiate a rupture or tear of the material or (2) propagate a tear in circumstances where continued application of a force on a suitable test specimen results in a quasi-equilibrium tearing action.

Nonreinforced membrane testing uses either ASTM D 624 Die C (rubber) or ASTM D 1004 Die C (plastics). These methods determine the maximum force required to initiate a tear in a right angle test specimen. The results are calculated by dividing the tear force by the specimen thickness. A 1.50-mm thick nonreinforced membrane with a tear force of 35 N has a tear strength of 23.3 kN/m.

Reinforced membrane tear is determined by ASTM D 751 (tongue tear) using a specimen with a slit cut in the center of the specimen. The tear strength is an average of the five highest peak loads (not including the initial peak) registered during the separation of the tear. Tear strength is reported in units of force (N).

Tear strengths of nonreinforced membranes determined using either ASTM D 624 or ASTM D 1004 should not be compared to tear strengths of reinforced membranes determined using ASTM D 751 because the test methods are very different. Because most roofing tear failures start as punctures, the use of ASTM D 751 modified for the use of a 200 mm x 200 mm specimen is recommended. The larger specimen size will greatly reduce the possibility of the reinforcement cord pulling through the coating, which does not occur in an actual roof tear. Cord pull-through invalidates the test.

With tear strength (T) now reported in standard units of measurement for all membranes, classification values can be established based on performance levels:

- T4: 200 N or higher
- T3: 100 to 199 N
- T2: 50 to 99 N
- T1: Less than 50 N

Example: A membrane with an average tear strength of 75 N has a tear strength level of T2.

Puncture resistance—There are many puncture resistance tests that are referenced in sales literature for polymeric roofing membranes. They can be divided into two categories: dynamic tests using dropped or shot projectiles and low-speed or static tests using a slow-speed probe, such as Federal Test Method 2031-101C. Puncture resistance of roofing membranes can be dependent on the type of roof substrate under the membrane. Some puncture tests are performed on a membrane/insulation/deck panel.

Until recently, there was no consensus standard in the roofing industry for puncture resistance. In January 1995, ASTM published two test methods to determine the puncture resistance of roofing membrane specimens. ASTM D 5635[4] covers dynamic puncture, and ASTM D 5602[4] covers static puncture. The dynamic puncture test will probably be used more frequently than the static test though test data is being generated with both methods.

The test method states that "it can be used to compare the dynamic puncture resistance of a single type of membrane as a function of a variety of insulation substrates or, conversely, to compare the resistance of a number of membrane specimens on a single type of insulation." It is recommended that the puncture resistance level be determined over at least wood fiberboard, polyisocyanurate, and expanded polystyrene insulation types. A membrane may have different puncture resistance levels depending on the insulation type.

Although tentative, the classification of puncture resistance (P) is shown for discussion (test increments are 2.5 J):

- P4: 40 J or higher
- P3: 25 to 37.5 J
- P2: 10 to 22.5 J
- P1: 7.5 J or less

Example: A membrane punctures at 25 J over wood fiberboard, 10 J over polyisocyanurate, and 45 J over expanded polystyrene. It has puncture resistance levels of P3 (fiberboard), P2 (polyisocyanurate), and P4 (expanded polystyrene).

Flexibility—Flexibility is the property that allows a membrane to be bent or flexed without rupturing. A membrane that becomes stiff and inflexible is subject to cracking or rupture when a bending force is applied. Most membranes are flexible at room temperature (20° to 30°C) but stiffen and become inflexible at low temperatures. In cold climates, it is very important that a membrane retain its flexibility, or a rupture could occur if the membrane is stressed during periods of cold temperatures.

The recommended test procedure used to determine the low-temperature bending capability of coated fabrics is ASTM D 2136[1]. This test method works well with all polymeric membranes. The membrane test specimen is placed in a test jig and bent around a hinge. After the bend, the specimen is observed under 5X magnification for cracks. If no cracks are observed in three specimens, the membrane passes the test.

Flexibility (F) levels are determined by performing the ASTM D 2136 low-temperature bending test. The lowest temperature at which three specimens pass the test determines the performance level of the membrane:

- F4: -40°C or colder
- F3: -20° to -39°C
- F2: 0°C to -19°C
- F1: 1°C or warmer

Example: A membrane that passes the flexibility test at -20°C but fails at -40°C has a flexibility level of F3.

Dimensional stability—Dimensional stability is the ability of a membrane to retain its original dimensions during the product's service life. This property is also called linear dimensional change, and if it is a negative value, it is shrinkage. All of the ASTM specifications for membrane dimensional stability use ASTM method D 1204[2]. The test is performed by carefully measuring the dimensions of a test specimen, heat aging the specimen, and then remeasuring to determine final dimensions. The dimensional change is calculated, and the result is expressed as a percentage.

The aging conditions currently specified in the material standards range from one hour at 100°C to 670 hours at 116°C, making comparison of membrane dimensional stability performance impossible. This is unfortunate because dimensional stability is a very important property of a roofing membrane.

Retaining ASTM D 1204 as the test method but standardizing the temperature and duration of aging is recommended. Although light-colored membranes will not initially become as hot as black membranes from solar heating, they usually become dirty and can reach temperatures as high as 60°C.

Performance levels are based on a maximum dimensional change of ± 2 percent after exposure to standard aging conditions. The dimensional stability (D) performance level must be maintained in both directions of the specimen. An alternate aging condition is shown for membranes that may be distorted at the higher temperature:

- D4: four weeks at 100°C or 16 weeks at 80°C
- D3: two weeks at 100°C or eight weeks at 80°C
- D2: one week at 100°C or four weeks at 80°C
- D1: two weeks at 80°C

Example: A membrane shrinks 1.5 percent in the lengthwise direction and 0.75 percent in the crosswise direction after two weeks at 100°C. Its dimensional change is more than 2 percent after four weeks at 100°C. The membrane has a dimensional stability performance level of D3.

Other properties—There are many other membrane properties that have the potential to become fundamental performance properties depending on the particular roof system design or an unusual environmental condition. They are shown here to use as a checklist. Roof system performance is dependent on membrane performance, but other roof system components (e.g., fasteners, insulation, and deck) are also important. These properties include:

- Abrasion resistance—Heavy foot or machine traffic across a roofing membrane can cause abrasion wear though walkway pads or rolls are recommended in these areas.

- Aesthetics—Some roofs, particularly those with white or colored membranes, are part of the building's overall appearance. Resistance to dirt pick-up, discoloration, and biological defacement must be considered.
- Biological resistance—Mildew, algae, fungi, and other organisms will live on the membrane surface and in ponded water on the membrane if conditions are favorable for their growth. Under these conditions, the membrane must maintain its properties and not be degraded by biological organisms.
- Chemical resistance—Chemical plants, food processors, laboratories, etc., can expose the membrane to unusual environments where periodic or continuous contact with acids, bases, salts, solvents, fuels, or oils will occur. The membrane must maintain its fundamental performance properties in this environment.
- Fire performance—The fire performance of a roof system is dependent on all of the major components in the system. In special circumstances, a flame-retardant membrane may be required.
- Water vapor transmission—All roofing membranes are expected to prevent water from entering the building. Most polymeric membranes are vapor barriers because they have a permeance less than 1 perm. Some special applications, such as cold storage warehouses, may require perm ratings much less than 1 perm. Membranes are available with permeances less than 0.05 perms.
- Wind uplift—Uplift performance of the roofing membrane is system-dependent, and all components (e.g., fasteners, insulation, and membrane) need to have minimum performance levels. The fundamental performance properties of strength (S), elongation (E), and tear (T) are particularly important for membranes used in mechanically fastened roof systems.

Environmental Aging/Weathering

The fundamental performance properties must remain at levels above the design requirements of the roof system both initially and during the design service life of the membrane. Problems begin when design requirements exceed one or more of the fundamental performance properties of the membrane. An example of this is the recent shattering phenomena of a specific type of nonreinforced membrane in cold weather. When the membrane was installed, its performance properties probably exceeded the design requirements of the roof system, and it functioned well as a watertight membrane. During the normal process of weathering, one or more of the fundamental performance properties (e.g., flexibility and dimensional stability) fell below the requirements, and the result was major membrane (and roof system) failure.

Laboratory aging and weathering tests are designed to accelerate the effects of normal real-time weathering without causing changes to a membrane that would not occur during outdoor weathering. These tests include heat aging, ozone exposure, and artificial ultraviolet (UV) weathering. The fundamental performance properties are determined before and after the aging/weathering exposure. If all of the performance properties remain at the original level (e.g., original is S4 and aged is S4) or improve (e.g., original is S3 and aged is S4) after aging/weathering, then it is highly probable that the membrane will perform as designed. If one or more of the properties moves to a lower performance level after aging, then caution must be used before selecting the membrane.

Heat aging—Heat aging is performed to simulate the effect of long-term elevated temperatures on the membrane. Solar radiation is absorbed by the membrane and converted to heat energy, which results in a temperature increase. Light-colored membranes remain cooler than dark-colored membranes, but it is important to perform a heat aging test on these, also, because of dirt pick-up, discoloration, etc.

ASTM heat aging tests for polymeric membranes range from seven days at 90°C to four weeks at 116°C for black EPDM. Some standards do not even require heat aging! The heat aging (HA) performance level of the membrane is the most severe heat aging that the membrane can endure while maintaining the fundamental performance property levels of an unaged membrane. All fundamental performance properties are determined after aging except dimensional stability. An alternate lower temperature can be run if the higher temperature causes distortion of the membrane. Heat aging performance levels are as follows:

- HA4: four weeks at 100°C or 16 weeks at 80°C
- HA3: two weeks at 100°C or eight weeks at 80°C
- HA2: one week at 100°C or four weeks at 80°C
- HA1: two weeks at 80°C

Example: A membrane has original performance levels of S4, E2, T3, P3, F4 and D2. The most severe heat aging that it can withstand while maintaining its original fundamental performance levels is one week at 100°C. Heat aging for two weeks at 100°C causes the flexibility to drop from F4 to F2 and elongation to drop from E2 to E1. This membrane has a heat aging performance level of HA2.

Artificial UV weathering—Laboratory weathering is generally done with a carbon or xenon (arc) weathering machine or fluorescent/ultraviolet condensation exposure apparatus. ASTM material specifications for polymeric membranes specify xenon-arc or fluorescent/UV condensation. Both machines expose the membrane specimens to heat, ultraviolet radiation, and moisture. The xenon-arc machine uses water spray, and the fluorescent/UV equipment exposes the specimen to condensing water vapor.

The recommended method for artificial weathering is to use the xenon-arc apparatus (ASTM G 26[5]) operated under the following conditions:

- Simulate natural sunlight by using Suprex filters in the air-cooled unit and borosilicate filters in the water cooled unit.
- Irradiance: 42 to 84 W/m^2 @ 300-400 nm.
- Cycle: 690 minutes of light, then 30 minutes of light plus water spray.
- Black panel temperature: 80° ± 3°C.
- Relative humidity: 50 ± 5 percent.
- Specimen rotation: every 37.8 MJ/m^2 @ 300-400 nm.
- Spray water: deionized, with standard spray nozzle in the air-cooled unit and F80 nozzles in the water-cooled unit.

After exposure, the specimens should be inspected for cracks under 10X magnification, as well as for chalking. Cracks and/or chalking is an indication that the surface of the membrane is degrading. Inspection for cracks must be done while the specimen is under a 10 percent strain.

The artificial weathering performance level of the membrane is the most severe weathering that the membrane can endure while maintaining the fundamental performance properties of a new membrane. Because of the limited size of the weathering chamber, it is acceptable for testing only strength (S), elongation (E), and flexibility (F). If strength, elongation, and flexibility are maintained, then it is highly probable that tear (T) and puncture (P) properties will also be maintained. If there is concern about tear and puncture, then these properties should be tested.

Weathering (WE) performance levels are based on total radiation exposure measured in J/m^2 rather than exposure hours. This allows for use of xenon-arcs that irradiate at different rates. These performance levels are:

- WE4: 604.8 MJ/m^2 @ 300-400 nm with no cracks under 10X magnification
- WE3: 453.6 MJ/m^2 @ 300-400 nm with no cracks under 10X magnification
- WE2: 302.4 MJ/m^2 @ 300-400 nm with no cracks under 10X magnification
- WE1: 151.2 MJ/m^2 @ 300-400 nm with no cracks under 10X magnification

Example: A membrane has original performance levels of S4, E2, T3, P3, F4, and D2. After WE4 exposure, the specimen's strength, elongation, and flexibility are maintained at S4, E2, and F4 levels. Based on this, the weather performance level is WE4.

Ozone resistance—Ozone is present in the atmosphere in concentrations that are high enough to cause cracking in certain types of polymer-based membranes. In roofing membranes, ozone does not reduce performance properties until it causes cracking of the membrane in areas that are under stress. If ozone cracking continues in susceptible membranes, however, a rupture may occur, allowing water to enter the roof system.

Because performance properties are not affected by atmospheric ozone until cracking occurs, the test only involves exposing a membrane sample to ozone, then inspecting for cracks. The ozone chamber should be maintained at 40° ± 2°C with an ozone concentration of 100 mPa in air. Nonreinforced specimens should be exposed and inspected under 50 percent strain. Reinforced and nonreinforced membranes that are difficult to stretch should be exposed and inspected while bent around a 75-mm diameter mandrel. Roofing membrane test specimens must be crack-free after a four-week exposure. This performance is classified as OZ4.

The Classification System

Fundamental properties and environmental aging/weathering performance categories are established and defined from higher (4) to lower (1) levels:

- Strength: S4 to S1
- Elongation: E4 to E1
- Tear: T4 to T1
- Puncture: P4 to P1
- Flexibility: F4 to F1
- Dimensional stability: D4 to D1
- Heat aging resistance: HA4 to HA1
- Weathering resistance: WE4 to WE1
- Ozone resistance: OZ4

The performance of a roofing membrane can be described by combining all of the individual performance levels into one grouping or line call-out. Obviously, a high performance membrane will contain mostly "4s" in its line call-out designation.

The most important aspect of this classification system is determining what is needed in a membrane based on system design requirements and environmental exposure conditions. For example, it would be a poor decision to specify an F2 membrane (becomes inflexible at -20°C for a roof system in Alaska where wintertime temperatures can fall below -30°C. Conversely, it would be unwise to chose a black membrane with a heat aging level of HA1 for a roof in Phoenix, Ariz., where summer temperatures can exceed 45°C.

Example—A black reinforced membrane is required for a mechanically fastened roof system in Denver, Colo., where the high elevation and summer heat require outstanding weather (UV) and heat resistance. Summer hailstorms occur periodically, requiring high puncture resistance, and winter temperatures require the membrane to be flexible to -20°C. Frequent high winds demand a membrane with high strength and low elongation. The roof system specifier decides that the membrane must have the following performance properties:

- Strength: 30 kN/m minimum (S4)
- Elongation: Less than 50 percent (E1)
- Tear: 100 N minimum (T3)
- Puncture: 40 J minimum (P4)
- Flexibility: Flexible to -20°C (F3)
- Dimensional stability: Highest level (D4)
- Heat aging resistance: Highest level (HA4)
- Weathering resistance: Highest level (WE4)
- Ozone resistance: Required (OZ4)

The description or line call-out for this membrane is:

S4 E1 T3 P4 F3 D4 HA4 WE4 OZ4

SUMMARY

Certain polymeric materials have properties that make them ideal for use as roofing membranes. The important properties include strength, elongation, tear, puncture resistance, flexibility, and dimensional stability. These fundamental performance properties can be measured using standardized test methods. The property values can be compared and grouped into distinct performance categories called levels.

The fundamental performance properties of the roofing membrane must be maintained over time as the membrane is exposed to environmental factors that include heat aging, ultraviolet weathering, and ozone. Aging and weathering tests can also be standardized for all membranes. The aging/weathering performance of the membrane is based on its ability to maintain the original fundamental performance property levels after all aging and weathering exposures.

The original properties and aging/weathering performance can be summarized by a line call-out designation that describes the performance level of the roofing membrane. Roof design requirements and environmental exposure conditions should determine the type of roofing membrane that is specified. A performance classification system would help roof system specifiers select membranes that meet these requirements and exposure conditions.

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