EVOLUTION OF PRESSURE-SENSITIVE ADHESIVES IN SINGLE-PLY ROOFING APPLICATIONS

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Introduction and Background

Single-ply polymeric roofing materials have dominated the commercial low-slope roofing market since vulcanized ethylene propylene diene terpolymers (EPDM) membranes were first engineered in the early 1970s. Before this time, most new construction was equipped with built-up roofs (BUR), consisting of alternating layers of asphalt and reinforcing felt materials. Polymeric single-ply membranes have the advantage of being very long-lasting, have the ability to cover large and unusually-shaped roofs (such as schools, shopping centers, and government buildings), and do not require large equipment investments by contractors for installation. In addition to EPDM, poly(vinyl chloride) (PVC) and thermoplastic olefin (TPO) membranes have also shared significant portions of the commercial roofing market, introduced to the US in the late 1970s and early 1990s, respectively. According to industry data, the total single-ply commercial roofing market was between three and four billion square feet in 2017. Neglecting bitumen BUR, the material market shares by square feet were approximately 23% EPDM, 17% PVC, and 60% TPO.

The primary application for pressure-sensitive adhesives in commercial roofing systems has historically been in seaming technology. During installation, sheets of membrane varying from six to 50 feet in width need to be joined side to side with a strong and waterproof bond. Depending on the membrane material, these bonds may be formed in a variety of ways. As thermoplastic materials, TPO and PVC are typically heat welded together. A piece of seaming equipment injects heated air at a temperature of 900°F (482°C) to 1,100°F (593°C) between the two membranes to soften the thermoplastic material, and then mates the two together with a heavy roller. The process results in a strong bond upon cooling to ambient temperature.

EPDM on the other hand, is not capable of heat welding and generally requires adhesive for the formation of seams. As EPDM grew in popularity during the mid-1970s, solvent-based neoprene or butyl rubber liquid adhesives became the norm for creating field seams. Although correctly applied liquid seam adhesive resulted in serviceable bonds between membranes, it was time-consuming to apply, tended to result in seams of inconsistent thickness, and was highly prone to applicator error. It was for these reasons that the attention of the roofing industry first turned to pressure-sensitive adhesives. In 1986 a permanently tacky transfer tape was introduced to the market. It was made of butyl rubber (isobutylene-isoprene copolymer) or an EPDM/butyl rubber blend, extruded about three inches wide and 35 mil (0.035 in) thick onto a release liner, and fully cured. Non-curing and field-curing tape technologies were also evaluated. Although non-curing tapes had high initial tack and low enough modulus to completely wet out the EPDM surface, they typically had very poor resistance to creep under high ambient temperature conditions. Field-curing tapes had similar creep deficiencies on the roof during the period between application and full cure and were prone to cure prematurely during storage. Premature curing reduced tack and eliminated the flow properties necessary to wet out the EPDM membrane. The unpredictable nature of this premature cure proved to be an insurmountable obstacle to the progress of field-curing tapes.

Between the years of 1992 and 1994, the number of commercial roofing contractors using cured pressure-sensitive tape for EPDM seams increased by 25%. [*1*] Although liquid splicing adhesives are still commercially produced, tape seams are required by most major manufacturers on warranted roofing systems. Present pressure-sensitive offerings require extrusion of the aforementioned butyl/EPDM material up to 20 inches in width for application to membrane seams and a variety of pressure-sensitive accessories. Some innovative pressure-sensitive products have also recently been brought to the table by coating types of adhesives that have not previously been typical in the roofing industry.

The applications in which pressure-sensitive adhesives are used today can be grouped into four general categories. The first category, seaming technology, is where pressure-sensitive adhesives first entered the roofing market. Products in this category are relatively well-established and time-tested. The second, primary bonding, has been dominated by liquid solvent-borne adhesives for years but there are innovative new products in the space. Pressure-sensitive accessories are somewhat of an extension of the seaming technology and represent the third category. Finally, air and vapor barriers are becoming more important with increased focus on green, energy-efficient building, and are typically provided with a peel and stick adhesive for easy installation. The intention for this paper will be to outline the demands on adhesives in each of these categories, the materials that comprise the adhesives, and the testing protocols that have been established for effective lab and field evaluation.

Seaming Technology

Most membrane sheets, whether EPDM, TPO, or PVC, are six to 50 feet wide by 100 to 200 feet long and require watertight seams where they are overlapped side to side, or sometimes end to end. All TPO and PVC membranes are seamed with heat welding, so we will focus on EPDM membranes in this section. We will revisit the use of pressure-sensitive products on thermoplastics during the discussion of roofing accessories.

There are two primary methods by which single-ply EPDM membrane is attached to a low-slope commercial roof, and the attachment method affects the demands on the seam. Fully-adhered systems are attached to the underlying substrate with adhesive across the entire field of the roof, as shown in Figure 1. Seam widths vary between three and six inches, with wider seams typically showing higher shear resistance and durability. In contrast, mechanically fastened systems lack adhesive between the roof and underlying substrate. Instead, they are attached by fasteners with metal or plastic head plates driven through the membrane, insulation, and roof deck at prescribed intervals. Mechanically fastened systems require the use of fabric-reinforced membranes to provide additional tear resistance at the fastening points. On a mechanically fastened roof, the seams serve an additional purpose of sealing the fastener penetrations to water entry as shown in Figure 2. Six inch seams are required to allow enough tape to seal around the perimeter of the fastener plates, and because reinforced EPDM membrane is typically more difficult to adhere to due to its rigidity and uneven surface.

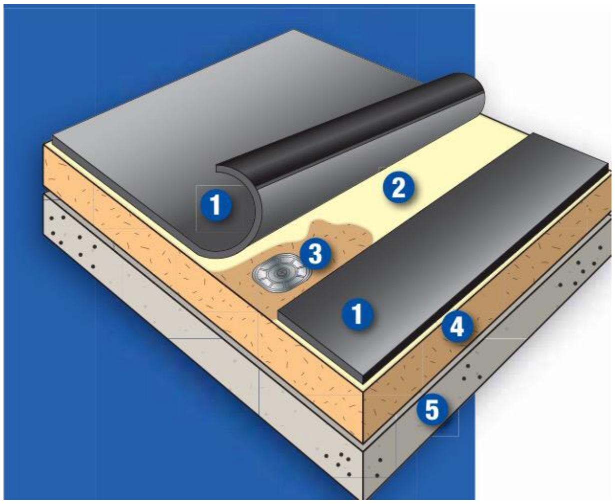

Figure 1. Diagram of a fully-adhered EPDM roof system showing (1) EPDM membrane, (2) bonding adhesive, (3) fastener plates, (4) insulation, and (5) roof deck. The tape on the top piece of membrane will create the seam over the bottom membrane.

Figure 2. Diagram of a mechanically fastened EPDM roof system showing (1) EPDM membrane, (2) fastener plates, (3) insulation, and (4) roof deck. The tape on the top piece of membrane will create the seam over the three fastener plates in the bottom membrane.

When considering the described systems, it becomes clear that seam adhesives may be required to adhere to a variety of substrates. EPDM membrane itself is a low surface energy material, with surface energies cited between 29.4 mJ/m^2 and 36.8 mJ/m^2 as tested by contact angle at 20°C. [*2*] The surface is also likely to be soiled by dirt, pollen, construction debris, or factory-applied dust. Mechanically fastened systems like the one pictured in Figure 2 will additionally require adhesion to steel or plastic fastener plates within the seams. Temperature is also an important variable at the time of application. Although the roofing busy season is typically during the summer, some roofs are installed during the winter months. On an installation in Minnesota during January, seam adhesives may be required to maintain their tack at temperatures down to 0°F (-18°C). In contrast, the temperature of a black EPDM membrane during July in Arizona may reach almost 180°F (82°C). It becomes challenging to design an adhesive that has sufficient tack at low temperatures, but enough cohesive strength under high heat conditions to maintain its integrity.

The conditions a roof seam is exposed to during its service life of over 30 years can be even more problematic. Elastomeric membranes are used for roofing all over the world, and the generally accepted service temperature extremes are around -80°F (-62°C) up to 220°F (104°C). As the membrane expands and contracts with temperature, an appreciable amount of stress on the seam can be expected. EPDM can also be expected to contract up to an additional 2% during its service life due to weathering. [*1*] For a typical 10 foot wide sheet of membrane with a three inch seam, a 2% contraction would be an opposing movement of about 1.2 in on either side of the seam. If the seam adhesive were completely viscous with no elastic properties, the seam would be expected to pull apart 2.4 in total or 80% of the bonded width. The shear resistance and elasticity of the seam adhesive is consequently very important. In mechanically fastened applications, the cohesive strength of the adhesive must also be considered because strong winds can billow the field of the membrane upward putting excessive stress on the seam and the fasteners within it.

Some parts of a roof regularly experience standing water. Additionally, EPDM membranes and the corresponding adhesives are often used as pond lining materials for ornamental water features. It is vital that the seam adhesive is not only watertight for building protection, but also resistant to degradation by standing water. Other foreign materials that may result from activities within the building are also potential degradants to the roof and seams. Although EPDM is not generally recommended for roofs that may be exposed to solvents, greases, or oils, short-term contact is not out of the realm of possibility. When there is particular concern about exposure conditions, the roof may be equipped with secondary waterproofing like a cover strip, which will be discussed in the accessories section.

The present industry standard for EPDM field seams is similar to the technology introduced in the 1980's: a cured butyl or EPDM transfer tape that is extruded to three or six inch width on a film or paper release liner. Butyl rubber is common in tape adhesives because of its hydrophobicity and its ability to flow to wet out the membrane. The tape generally requires application of a solvent-based primer to both membrane surfaces before forming the seam. The primer serves as a cleaning agent to remove dust and debris from the seam area, and to modify the surface of the EPDM by raising its surface energy. Liquid seam adhesives that cure upon drying are still sold, but are generally only used for non-warranted work or small repairs. According to a 1996 NIST study that tested liquid adhesives and tape systems from various manufacturers, tape had much more reproducible results compared to liquid adhesives, particularly in shear testing. The variability in the liquid adhesives may have been a result of "cellular microstructures" or bubbles within the cured layer, identified by scanning electron microscopy. [*3*] The thickness of EPDM seam transfer tape typically ranges from 25 mil (0.025 in) to 40 mil (0.040 in). A similar NIST study in 1997 examined the effects of material and application factors on the peel and shear strength of tape systems. Thicker tapes (between 0.035 in and 0.040 in) showed consistently longer time to failure on dead load shear tests than thinner tapes (between 0.020 in and 0.025 in). [*4*]

There have been some notable changes with seam technology in recent years. The two most important developments have been EPDM membrane with tape pre-applied by the manufacturer and white seam adhesive. EPDM membrane with tape pre-applied by the manufacturer has two distinct advantages. The first is that it affords the roofing contractor a labor-savings by cutting in half the amount of priming and taping that needs to be done in the field. It also improves the quality of the seam because some of the application is done in a controlled, clean environment with even primer coverage and bonding pressure. EPDM membrane with tape pre-applied by the manufacturer was first introduced in 2002 and currently makes up about 30% of all EPDM membrane sold by one manufacturer. White seam tape was introduced in 2000 for use on white EPDM membranes. Because it was developed for aesthetic reasons, white seam tape takes on the added burden that it must not stain or discolor over its service life. It is generally formulated with similar polymers to black seam tape, but with silica instead of carbon-based fillers. These fillers have different reinforcing characteristics and can affect the physical properties of the formulated adhesive if loading levels are not carefully considered.

Roofing seam tapes and primers are typically tested as a system in a variety of testing protocols, including industry standard dynamic peel and shear tests. Instead of discussing the details of these well-known tests, I would like to highlight a few particularly important and unique tests used in the roofing industry. The shear adhesion failure temperature (SAFT) test, similar to the method outlined in PSTC-

17 [5], is often used to evaluate the shear performance of seam assemblies (shown in Figure 3) under elevated temperature conditions. Tape-bonded samples are hung in shear geometry and then the temperature is increased at a steady rate from 10°C (50°F) to 150°C (302°F) or until failure. In combination with elevated temperature dead load shear tests, the SAFT is very useful for modeling the stress and temperature conditions a seam may experience in the field.

Figure 3. Shear Adhesion Failure Temperature (SAFT) samples suspended for testing in an environmental chamber.

A more practical test that is often used to test seam assemblies for water tightness, particularly at overlapping seams, is the bucket test. In this test, a piece of membrane containing a seam is fastened and sealed to one end of a cylinder. With the membrane end down, but elevated above the work surface, the cylinder is filled with water and the seam monitored for leakage due to hydrostatic pressure.

After laboratory testing, large-scale testing of the full roofing system is typically the next step before commercialization of a product. Wind uplift testing is common to the roofing industry. Bernoulli's Principle states that an increase in fluid (or air) velocity over a surface results in a decrease in surface pressure. Such a decrease results in a pressure differential between the inside and outside of a building, and an upward force on the roof. [6] A wind uplift test typically exerts increasing positive pressures under a 12 foot by 24 foot roof assembly that is sealed around the edges. Ten foot wide membrane sheets are used so that multiple seams are incorporated across the assembly. Building codes equate wind uplift holding pressures to system wind speed ratings. Mechanically fastened systems are usually used in wind uplift testing for seam assemblies because the billowing of the membrane exerts increased stress on the seam as seen in Figure 4, and creates a worst-case scenario for the seam adhesive. In this type of system, a failure is usually indicated by fasteners pulling up out of the substrate or fastener plates pulling through the membrane in the seam areas. Seam separation is also a potential failure mode, but typically does not occur under normal conditions.

Figure 4. A white mechanically fastened roof undergoing a wind uplift test. The fasteners are visible within the seams. [*7*]

Primary Bonding

A primary bonding adhesive attaches the entire field of the roofing membrane to the substrate below it in a fully-adhered system. The bonding adhesive market has traditionally been dominated by solvent-borne contact adhesives that are comprised of synthetic rubber, polychloroprene, and/or a variety of block copolymers. “Peel and stick” self-adhering membranes have, however, come to find a place in the roofing market as a premium product. Self-adhering membranes typically save the roofer time and are more environmentally-friendly because they do not contain solvents.

Adhesives for primary bonding applications are subject to even more application challenges than those for seaming. Most notably, the variety of substrate combinations for primary bonding adhesives are dramatically higher. In addition to EPDM, primary bonding adhesives are used to adhere TPO and PVC membranes. On the field of the roof, the adhesives will be required to stick to paper or coated glass insulation facer, gypsum board, concrete, and metal facers or curbs. In some applications, the adhesive may also be applied directly to plywood, polystyrene insulation, or existing roofing. For solvent-borne adhesive, there is also significant consideration given to the interactions that solvents might have with the substrate materials. Plywood and paper facer, for example, have considerable ability to absorb or wick solvent by capillary action. Some solvents can also lead to cavitation of polystyrene or polyisocyanurate foam insulation. Finally, the primary bonding adhesive must not lead to negative interactions with other adhesives or sealants used in the system.

A number of challenges have come against the traditional solvent-borne bonding adhesives, particularly since the passing of the Clean Air Act of 1990 and subsequent creation of the Ozone Transport Commission (OTC). The most significant regulatory push has been by the OTC to reduce or eliminate volatile organic compounds (VOCs) because of their contributions to ground-level ozone and smog. These regulations affect primarily the Northeast and Mid-Atlantic states. Parts of California are governed by a separate, more stringent set of regulations enacted by the South Coast Air Quality

Management District (SCAQMD). Even in non-OTC states, complaints about the odor of solvent-borne adhesives from roofers and building occupants are not uncommon. For these reasons, a number of solvent-free adhesives have been introduced into the bonding adhesive market. Purely water-borne adhesives have struggled to find footing because of their propensity to thicken or freeze in cold application temperatures. Applicators also find the increased drying time of water-borne adhesives to be unacceptable compared to solvent-borne alternatives. Urethane foam and 100% solids adhesives have a significant market share, but are not appropriate for all applications and come with their own challenges. This situation reveals an opportunity for pressure-sensitive adhesives in the primary bonding space. Major roofing manufacturers offer self-adhering EPDM and TPO products with pre-applied pressure-sensitive adhesives, and the popularity of these products are expected to increase in coming years.

In testing pressure-sensitive adhesives for primary bonding, shear adhesion is less important on the field of a roof, but becomes of greater consequence when adhering to the vertical surface of a parapet wall. SAFT testing is routinely performed during the development of bonding adhesives, pressure-sensitive or otherwise, and as a tracking test for a number of commercial products. Similar to seam assemblies, wind uplift decks are also required for building code approval of new bonding adhesives in fully-adhered systems. Wind uplift failure in this circumstance could be indicated by blisters of uncontrolled growth between the membrane and underlying substrate. Finally, we find that the field application trial is the only method that can expose certain adhesive issues like de-bonding and "mole tunneling" (shown in Figure 5) from expansion and contraction of the membrane.

Pressure-Sensitive Accessories

The same cured transfer tape that is used for seaming EPDM membranes is often used to fasten accessories to the surface of the roof with a waterproof bond. EPDM accessories generally come with tape pre-applied and could be loosely grouped into two families: laminated accessories (including cured and uncured flashings, cover strips, and reinforced product for securement at the roof perimeter and at penetrations), and molded products (including walkway pads and pipe seals).

Figure 5. "Mole tunneling" that can result from the thermal expansion and contraction of roofing membrane after installation.

There are also some laminated products that are specially pre-cut for particular purposes, such as inside and outside corners. Like membrane with tape pre-applied by the manufacturer, these accessories increase consistency of performance and save time for the applicator.

Some accessory products do, however, come with additional adhesive challenges above and beyond a general EPDM seam. The uncured EPDM that is used for flashings, corners, and patches is susceptible to more significant thermal expansion than cured membranes, leading to even more stress on the bond between the uncured material and the adhesive layer. Some of these accessories are also typically applied in awkward locations, stretched over corners or intersecting with seams as shown in Figure 6. In these applications it is important that the primer and tape system is able to create an instantaneous bond to the membrane with an appreciable amount of green strength. Manufacturing and laminating processes also differ between cured and uncured EPDM products, so the all-purpose adhesive must have robust performance under a variety of processing conditions.

There has been recent demand for pressure-sensitive products that work with thermoplastic roofing systems. Although heat welding remains the preferred method for creating field seams, some applicators find peel and stick accessories to be a time savings over welded versions. Major roofing manufacturers have offered TPO cover strip, a non-reinforced strip of TPO membrane laminated with pressure-sensitive adhesive, for some time. The adhesive is typically the same one used for white EPDM applications, but a modified primer may be used to accommodate for the surface characteristics of the TPO membrane. Within the past several years, system specifications have also begun to allow the use of other EPDM accessories with TPO systems. Pressure-sensitive accessories for PVC systems have been slower to market because of the effect membrane plasticizers can have on the adhesive.

Figure 6. Uncured pressure-sensitive flashing used to seal the outside corner of a curb to the roof deck. Two pieces of flashing are used with multiple overlapping seams. Sealant has also been used around the edges of the flashing.

Air and Vapor Barriers

With increasing interest in Leadership in Energy and Environmental Design (LEED) certification for new construction from the U.S. Green Building Council, air and vapor barriers are becoming more common. Such materials are used in numerous locations throughout the building envelope to keep conditioned air inside buildings and to prevent the transfer of moisture into breathable materials like drywall and insulation. Considering the scope of this paper, we will consider only rooftop applications. Air and vapor barriers are typically applied below the insulation, directly against the deck of a roof. This prevents moisture from entering and condensing inside the insulated space between the deck and the roofing membrane. Although air and vapor barriers are occasionally used on all types of roofing systems, they are more commonly required on mechanically fastened systems. The same products are also marketed as temporary covers to waterproof partially-installed roofs during construction.

Substrate possibilities for air and vapor barriers are similar to those for primary bonding adhesives and include low surface energy TPO and EPDM membranes. Direct application to steel roof decking is, however, much more likely with the barriers. They also have the added requirement that their upper surfaces be good substrates for application of other adhesives. Products can be composed of a number of materials. One commercial product consists of an approximately 35 mil (0.035 in) thick layer of SBS-rubberized asphalt laminated to a 5 mil (0.005 in) thick woven polypropylene film. Asphaltic materials are common in this application because of their flexibility, water-resistance, and ability to flow and conform to rough substrates like wood or textured steel. Thick layers of adhesive are also typically beneficial in this circumstance.

Another temporary pressure-sensitive product has found use as a protective covering for white thermoplastic membranes. Thermoplastic membranes are supplied from the manufacturer with a pre-applied liner adhered to the top by a thin layer of removable pressure-sensitive adhesive. The liner protects the top of the white membrane during installation and is intended to be removed when work is complete as shown in Figure 7. This offers another time-savings to the applicator because the surface does not require cleaning after installation. The liner is also textured to reduce glare and improve footing during installation. The adhesive is specifically engineered to have strong anchorage onto the removable film, but release cleanly from the thermoplastic membrane upon removal.

Figure 7. Protective liner being removed from a completed thermoplastic roof.

Conclusion

In summary, the pressure-sensitive adhesive tape is an important technology in the commercial roofing market and one that will continue to grow in its range of applications. PS adhesives serve four main functions within roofing systems: seaming technology, primary bonding, pressure-sensitive accessories, and air and vapor barriers. Each application presents a different set of performance requirements. Some common challenges include the variety of substrates, high degree of temperature variation in both application and service environments, inconsistency in application methodology, and high shear stress due to wind conditions. A variety of laboratory testing protocols are used to simulate service conditions and evaluate adhesives accordingly. Small-scale techniques include SAFT and bucket tests, while large scale system techniques include wind uplift tests and trial installations.

The demand for pressure-sensitive adhesives in commercial roofing will likely increase as regulatory pressure on traditional adhesives rises and building owners and designers become more environmentally responsible. Thermoplastic roofing materials also account for 75% of the market and expanded pressure-sensitive offerings for these systems certainly represents an immense growth opportunity. Finally, according to professional organizations like the Association of General Contractors (AGC), contractors are experiencing a severe shortage of skilled labor in certain parts of the country. A survey in 2015 reported that as many as 56% of roofing contractors are having difficulty filling positions. [*8*] Pressure-sensitive peel and stick membranes and accessories afford significant time savings and are easy to use, a win for the contractors and applicators alike. For these reasons, pressure-sensitive adhesives will become an increasingly beneficial fit for the roofing market.

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Acknowledgments

Thank you to my colleagues who helped develop this material:

Mike Scanish, Adhesives R&D Manager, Carlisle Construction Materials

Bill Schneider, EPDM R&D Manager, Carlisle Construction Materials

Ron Goodman, Product Marketing Manager, Carlisle Construction Materials

And to the Pressure-Sensitive Tape Council for supporting this presentation.