Performance Properties of Interply Adhesives Used with SBS-Modified Bitumen Membranes 2007 Update

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ABSTRACT

Application alternatives for adhering SBS (styrene-butadiene-styrene) modified bitumen sheet materials include hot mopping asphalt or bitumen, heat welding , liquid cold process adhesive, and self-adhesive. When SBS-modified bitumen roof membranes were introduced in the United States in the late 1970s, the majority of the North American contractor base was built-up roofing oriented. Familiarity with hot asphalt application and practicality of dealing with existing equipment made installation of SBS-modified bitumen membranes in hot oxidized asphalt an easy choice. The early history with SBS-modified bitumen systems in Canada reveals that torch applied SBS membranes were more popular. Laboratory testing and field experience have demonstrated that solvent-based (cold) adhesives, heat welding, and heat-activated self-adhesives offer higher interply performance than oxidized bitumen. Across North America, torching applications have come under the increasingly heavy scrutiny of the insurance industry, and there have been historic shifts in the world of petroleum refining. Some fundamental characteristics and performance differences of various types of interply attachment methods specific to SBS-modified bitumen roof membranes will be updated in this paper. As a result, practical considerations in choosing the appropriate application method will be addressed.

INTRODUCTION

This paper is a follow-up to work presented at the NRCA/BWA 12th International Roofing and Waterproofing Conference in September 2002.[1] Although there have been no revolutionary changes in the modified bitumen industry since that time, recent events have altered the landscape of the roofing industry: dramatic increases in crude oil prices, building code revisions, energy code implementations, updates to FM Global wind uplift criteria, and more stringent torch safety requirements - just to name a few.

Product design, modified bitumen formulations, adhesive formulations, and application techniques have evolved since 2002. Driven by VOC regulations, labor considerations, relative installation costs, and market shifts, new or updated technologies for cold adhesives and self-adhesives have emerged in the last five years as well. While giving the user a larger universe of materials from which to select, the decision making process is further complicated. Which modified bitumen membrane should be used with which interply adhesive? In what conditions may cold adhesives and/or self-adhesive be applied? What substrates are acceptable, and what type, if any, primer is required for self-adhesive or “cold” applied sheet materials? The content of this paper will attempt to clarify some of these questions with recently obtained supporting data.

Mopping Bitumen

Although oxidized mopping asphalt remains a healthy portion of the market for adhering SBS-modified bitumen in the United States, no new testing was conducted in this study. Due to the high cost, and shifts in supply origin of crude oil compared with 2002, one would expect that there is more variability today with regard to mopping asphalt quality. ASTM D 312, Type IV asphalt was tested and data presented in the 2002 NRCA/BWA proceedings. Variability in quality was established in the 2002 data, and thus the data remains valid for comparative purposes in the current work. Users should be very conscientious in requesting technical certifications for each shipment of material from the mopping asphalt suppliers. More importantly, users should insist that SBS-modified bitumen producers approve or accept the use of specific mopping asphalt supplies, by asphalt plant location, to ensure that the mopping asphalt of choice is considered compatible with the modified membrane being installed. Such steps increase the likelihood of long-term satisfaction with the hot asphalt applied SBS roof membrane system.

While not specifically addressed with data in this writing, modified mopping bitumen is occasionally used to install SBS-modified bitumen sheets. Typically modified with synthetic rubber such as SEBS, modified mopping bitumen offers superior performance characteristics as compared to oxidized bitumen. There are numerous suppliers and qualities of modified mopping bitumen, and the variations are too involved to adequately address here. Briefly, modified mopping bitumen is an improvement compared to oxidized bitumen, however many considerations are the same if not more critical: compatibility with the SBS sheet materials, short and long-term product quality of the bitumen matrix, kettle heating conditions and duration, application temperature limitations, and of course the unwieldy process of the mopping application itself. As with the selection of other roof system components, consultation with the membrane manufacturer is essential when considering the selection of appropriate modified mopping bitumen.

Heat Welded (Torched)

The term heat welded, rather than torched, modified bitumen is preferred because it more accurately describes the end result. Heat welding may be accomplished with an open flame torch or by using various types of electric or gas powered hot air welding devices specifically designed for modified bitumen applications. This method of attachment is the only means of achieving a truly monolithic multiple ply roof membrane when two or more layers of modified sheets are installed. The modified bitumen coating on the sheets literally fuses together, forming one contiguous sheet membrane.

Modified bitumen roof membranes have been heat welded in Europe for more than 35 years, in Canada for more than 30 years, and in the United States for more than 25 years. Certain SBS-modified bitumen sheet goods are available with specifically designed, patented surface treatments intended to enhance heat welding and make the products more efficient to install; see Illustration 1.

Open flame torching, however, has been under scrutiny due to both the real and perceived fire risks associated with this practice. In 2004, the NRCA and MRCA devised a new CERTA (Certified Roofing Torch Applicator) program at the behest of the insurance industry. FM Global Property also addresses this issue in their Property Loss Prevention Data Sheet 1-33 *Safeguarding Torch-applied Roof Installations*. Local building codes sometimes ban torching, and some companies invoke no-torching policies on their buildings. Now, some specifiers shy away from it. The most challenging hurdle for the future of torch application is the rising cost of insurance for the roofing contractor. Even in Canada, where torching of SBS-modified bitumen has been the norm for almost 30 years, the rising cost of insurance is forcing contractors to take a strong look at alternative application methods.

Theoretically it is impossible to improve upon the interply bond strength of properly heat welded membranes. When heat welded correctly, the rubberized (SBS) or plasticized (attactic polypropylene (APP)) asphalt compound on adjoined sheets becomes one homogeneous layer of modified bitumen. This in essence yields the ultimate composite condition for a modified bitumen membrane: an interply weld comprised of fused modified bitumen compound from both sheets. As with any application technique, mistakes can be made when torching or heat welding. Under heating will not adequately fuse the sheets together, making interply blisters possible. Severe over heating certainly leads to poor aesthetics and potentially long-term performance problems. Keep in mind that SBS and APP are quite different polymer systems. SBS is an elastomer, or rubber, and APP is a plastic. Therefore their torching characteristics are not the same.[2]

Cold Adhesive

Cold process roof membrane adhesive is known by many monikers, some of which are not suitable for this publication. Terms such as “cold process”, “cold adhesive”, “solvent-based adhesive”, “cutback adhesive”, “mastic”, “cement”, “glue”, etc. are commonly used to describe this material.

Solvent-based asphalt cutback adhesives have been used in built-up roof systems in North America for more than half a century, but maybe less known is that they have also been used in the United States very successfully with SBS-modified bitumen roofing membranes for over 25 years. Virtually every supplier of SBS-modified bitumen now includes cold adhesives in their product line. Momentum for the use of cold adhesives began to rise prior to the 2002 NRCA/BWA conference, and that momentum continues today. One only needs to read the roofing trade press and visit modified bitumen suppliers’ Web sites for proof.

Although the make-up of cold adhesives used with SBS-modified bitumen sheets varies greatly, still the most common family of cold adhesives are solvent-based or cutbacks. The term cutback is used because the asphalt base is dissolved or “cut” with a solvent carrier. Cutback adhesive formulations include asphalt, solvent, fibers, fillers, and stabilizers. Some may contain polymers, resins, or other modifiers. Just as with mopping asphalt, not all cold adhesives are the same. Despite generally superior bonding characteristics as compared to hot asphalt, the same quality issues must be considered. For example, is the cold adhesive compatible for use with the specified modified bitumen membrane? The choice of solvent is a major factor in this regard, as solvents vary by aromaticity, boiling point range, flash point, etc. Commonly used solvents include various qualities of mineral spirits and naphtha. The base asphalt quality, together with the choice and blending of related fibers, fillers, and stabilizers is also critical due to the fact that this “solids” portion of the adhesive remains as the bonding agent when the solvent completely evaporates from the membrane assembly.

The term cold adhesive really is a misnomer. Upon review of suppliers’ and industry literature[2], one frequently finds that recommendations are given for warming the adhesive prior to use. The primary reason for this is to maintain proper viscosity for ease of application and maintaining the appropriate adhesive thickness rate – more is not better. Warming also improves the “wetting out” of the sheet materials with the adhesive, thus improving the bonded area and interply strength.

The specification and use of cold adhesive SBS roof systems was not as quickly or enthusiastically embraced in the Canadian roofing market as it was in the United States. Climate differences, successful performance of torch applied SBS systems, tradition, and waiting to see “how it worked” in the United States may help explain the lag time, all of which are quite legitimate reasons. In the near past, however, there has been an increased interest in cold applied roof systems in Canada. Drivers are similar, if not identical, to those experienced elsewhere. For various reasons, the use of hot mopping asphalt, torching, and to a lesser degree even cold adhesives may be restricted. Fumes from hot asphalt kettles prohibit hot mopping on many buildings such as schools, hospitals, office spaces, and the like, during any period of occupancy. This either leads to scheduling work around non-occupied times, or in most cases changing the application method altogether. Torching may be prohibited due to specific job circumstances, for insurance reasons, or simply because the building owner or specifier may have an aversion to this practice.

The use of cold adhesive is not exempt from limitations, but the limitations are usually less invasive. Solvent odor can be an issue for some adhesive materials, particularly those with high sulfur content, but the primary issue for cold adhesives is VOC regulations. In 2002, the area with the strictest VOC regulations was California with a maximum limit of 250 grams per liter (g/L), and it was stated that regulations pertaining to VOC content would be become more stringent in other areas of the United States within the next few years. New VOC regulations for the northeastern United States, outlined by the Ozone Transport Commission (OTC), followed the California lead. Changes to VOC requirements prompted advancements in adhesive formulations. Today, most cold adhesives for modified bitumen fall below the 250 g/L level. Because of the downward trend in VOC limits, the green strength, pot stability, and application viscosity continue to be tweaked.

Adhesives with very low, or no, VOC levels also exist. They can be very effective, but come with a price. Generally, they are 3 to 5 times more expensive than their cutback counterparts. One such very low VOC adhesive was included in the 2002 study, and the data did not demonstrably support any real performance advantage compared to less expensive "asphalt cutback" adhesives. The only perceived technical advantage could be that this product, which is a moisture-cured asphalt extended urethane, has better green strength in the first 24 hours than do cutback products. The long-term performance, however, was no better than less expensive adhesives. A new solvent-free adhesive option is available. It is a single component, moisture cured polymer modified asphalt unique in its ability to cure at lower temperatures than urethane-based systems. The primary benefit of this particular adhesive is that it can be installed on occupied spaces with the most sensitive of odor restrictions.

While it is true that solvent-based adhesives tend to soften the sheets during curing (or flash-off), with proper planning and job staging, difficulties associated with sheet softening can be minimized. This condition is merely temporary, and results herein depict the relative softness of one SBS sheet material applied with various interply methods. Low VOC does not necessarily mean that the adhesive will soften sheets less than a "high" VOC product; this is highly dependent on the solvent chemistry. There are trade-offs between the "cure" rates and green strength of cutback adhesives. For example, one manufacturer offers two cutback adhesives with very similar VOC – one softens the sheets less in warm weather, but does not setup or cure as quickly as its counterpart that cures much faster but softens the sheets more in warm conditions. Choices may now be made based on the installer's preference. Preference may be influenced by ambient conditions anticipated at the time of application, or field experience and comfort level may affect the choice.

In 1996, samples of a two-ply, fiberglass reinforced, cold adhesive applied SBS membrane were taken from a roof assembly installed in Ohio in 1982. When tested according to ASTM D 5849 *Cyclic Joint Displacement*, the 14-year old two ply membrane passed the requirement for newly installed membranes (500 cycles at -10^{o}C [14^{o}F]), far exceeding the requirement for aged materials, which is only 200 cycles. This roof membrane is still performing today, almost 25 years after installation.

As with any laminated construction, the glue line affects the performance of the finished product. Generally speaking, thinner glue lines lead to better performance. Cold adhesive application results in a much thinner glue line than hot asphalt applications. Most modified bitumen manufacturers ask for interply mopping weights between 0.98 and 1.46 kg/m^2 (20 and 30 lb/100 ft^2), or 1.0 to 1.5 mm (40 to 60 mils) respectively. For various reasons, actual interply mopping weights are often found to be in excess of these specified values. Cold adhesive interply usage is generally specified to be between 0.6 to 1.0 L/m^2 (1.5 to 2.5 gal/100 ft^2), which equates to 0.6 to 1.0 mm (24 to 40 mils) wet film. After solvent evaporation, this thickness is significantly less depending on the solvent content.

Most importantly, unlike hot asphalt that merely acts as a hot melt glue, there is a chemical bond (or type of solvent welding) that occurs when adhering modified bitumen sheets with compatible cold adhesive. Depending on the type of modified sheet and solvent system, the resultant bond is very similar to that achieved with heat welded or heat welded membranes. Because of the strength of this interply bond, the chances of long-term disbonding and blister formation are greatly reduced. Even if a small interply void exists, a blister cannot grow unless the internal pressure overcomes the bond strength of the interply attachment.[3,4,5,6]

In a 1988 report by Structural Research, Inc.[7] membrane factors for various SBS membranes including polyester, polyester/glass combinations, and fiberglass reinforced membranes were assessed. When using the same two-ply glass reinforced SBS membrane, cold adhesive and hot asphalt applications performed dramatically differently. One of the lowest membrane factors was that of the two ply SBS membrane installed with hot Type IV asphalt while the best performing system, of all reinforcement types, was the same two ply membrane installed with a compatible liquid applied cold adhesive. The membrane factor took several factors into account including coefficient of expansion and load strain properties at low temperature.

Self-adhesive

As expected, the use of self-adhesive (SA) SBS membranes for use in low-slope commercial, industrial, and institutional applications has increased since 2002, but arguably not at the rate predicted. There are many good applications for SA sheet materials, but there are also numerous cautions to be heeded when selecting and installing SA sheets.

This system consists of modified bitumen membranes coated with a “self-adhesive” bitumen formulation. These self-adhesive or peel-and-stick systems have their place. These products enjoy a burgeoning market for use as underlayment for steep sloped roofing, but this paper only addresses their use in low sloped applications. Unlike all the other methods for adhering modified bitumen, self-adhesives dispense with the need for any form of liquid adhesive in the membrane. As such, there are no fumes, VOCs, or flames on the rooftop. This is the benefit of self-adhesives. It also happens to be the drawback.

Since there is no form of liquid to wet and fully penetrate the surface of the substrate, or fill in the “step downs” at overlaps and T-joints, more care must be taken during installation. See Illustration #2. Whenever self-adhesive modified bitumen is installed in multiple layers, the overlaps and T-joints of all plies above the base ply must be treated with a sealant material to create watertight seams. An option to using sealant is to heat weld the seams.

Arguably the single biggest challenge for these products is the drastic change in modulus and adhesive properties of the self-adhesive bitumen compound with changes in temperature. Most manufacturers of self-adhesive modified bitumen list 10°C (50°F) as the low temperature limit. A few publish slightly lower application temperature limits. At temperatures below 10°C (50°F), the modulus of the self-adhesive bitumen is quite high and the tack properties suffer as well. Self-adhesive materials should be kept warm just prior to application in cool weather. Hot air equipment may also be used to warm the self-adhesive surface prior to installation.

Compared with conventional application techniques, adhesion for self-adhesive products is more dependent on the surface roughness of the substrate since there is no liquid to fill irregularities. In this case the membrane will bridge any gaps in the substrate surface. At the least, primer should be considered in all cases. Even when surfaces receiving the SA modified bitumen are smooth and regular, a slight film of dust can inhibit proper adhesion. Primers help alleviate this problem. Manufacturers' guidelines should be consulted in every case as self-adhesive formulations are as varied as any other product discussed herein.

Caution is recommended when installing self-adhesive products. The mentality and installation techniques are more akin to those of single ply roofing than conventional methods for installing SBS-modified bitumen. The product requires some finesse and pressure during application – this is not dissimilar to the application practices required for seaming EPDM membranes with butyl tapes. As long as manufacturers, specifiers, and contractors keep this in mind, self adhesives can be installed successfully.

Charts 1, 2, and 11: 2002, illustrate significant differences in peel strength of one SBS self-adhesive material adhered to plywood with various primers. They also depict different self-adhesive modified bitumens adhered to the cross-laminated HDPE surface of an underlying modified bitumen sheet. This was done to give a relative comparison of the adhesive quality of the self-adhesive layer on different sheets.

While some SA blends may be very sticky and attach quite readily to some surfaces, including another layer of SA blend, the bond may not be free of voids or capillaries. An important adage to remember with SA sheet materials is that their bond may be "tight" without being "watertight".

METHODOLOGY

Various tests were performed to examine the:

- Rotational viscosity of different liquid applied cold adhesives.
- Softness of SBS sheet material adhered with a variety of interply materials.
- Peel strength of various interply attachment methods.
  - During the "curing" or "flash-off" period.
  - After heat conditioning (artificial aging).
  - At two temperatures 23°C (73°F) and 50°C (122°F).
- Tensile bond strength of various interply attachment methods.
  - During the "curing" or "flash-off" period.
  - After heat conditioning (artificial aging).
  - At two temperatures 23°C (73°F) and 50°C (122°F).
- Cyclic joint displacement (fatigue) of the same two ply, glass reinforced SBS membrane adhered with various interply materials.

Sample compositions are listed below.

- All membrane/adhesive samples consist of two plies of SBS-modified bitumen sheet materials bonded with a "cold" adhesive.
- Two-ply torch applied SBS membrane.
- Compatible ASTM D 312, Type IV mopping asphalt between SBS base and SBS cap.
- Generic ASTM D 312, Type IV mopping asphalt between SBS base and SBS cap.
- Self-adhesive SBS membranes.

Viscosity

All samples except the mopping asphalt were tested at 23°C (73°F) using a Brookfield DVI+ rotational viscometer.

Sheet Material Softness

Interply adhesives were applied to one manufacturer's SBS-modified bitumen membranes in a two ply configuration just as with the other tests. Samples were conditioned at 23°C for 1, 3, 7, and 28 days. Some samples were conditioned at 70°C (158°F) for 7 days. Oven conditioned samples were allowed to cool for 2 hours at 23°C (73°F) prior to measuring the Shore O durometer hardness.

Peel Strength

Mopping asphalt data from the 2002 paper was tested using the SPRI 180° Peel Test (Method B). Method deviation: sample size 25 x 250 mm (1 x10 in). All other "T" peel data presented herein was tested according to ASTM D 1876 except a sample size of 63 x 250 mm (2.5 x 10 in) was used. Cold adhesive between sheets was applied at the rate of 0.6 ± 0.05 mm (24 ± 2 mils) wet film. Mopping asphalt was heated to 260 °C (500°F) before it was poured between plies. Self-adhesive membranes were rolled with a 11.8 kg (26 lb) roller three times back and forth in 5 seconds. All samples were conditioned at room temperature.

Tensile Bond Strength of the Interply

Tensile bond strength of the interply layer was evaluated using 150 x 150 mm (6 x 6 in) specimens. Materials were tested at several stages of the curing process, and after a 7-day oven exposure period. Samples were conditioned at 23°C (73°F) for 1, 3, 7, and 28 days. To simulate fully "cured" adhesive, oven conditioned samples were exposed to 70°C for 7 days before testing. Some samples were tested after heat conditioning for 30 and 60 days at 80°C (176°F).

Cyclic Joint Displacement (cyclic fatigue)

This test was carried out using *D5849 Standard Test Method for Evaluating Resistance of Modified, Bituminous Roofing Membranes to Cyclic Joint Displacement* under test condition # 4. Samples were adhered to solid wooden supports using epoxy glue. Samples were conditioned for 24 hours at room temperature. Sample composition consisted of two plies of 70 g/m^2 fiberglass-reinforced SBS membrane.

Heat Conditioning (oven aging)

Samples tested in 2002 and 2007 were conditioned according to ASTM D 5869 *Dark Oven Heat Exposure of Bituminous Materials*, except with a temperature of 80°C (176°F), for up to 90 days.

RESULTS

Viscosity

The high VOC adhesive "A" and the low VOC adhesives "B, C and D" are known to apply easily using squeegee, spray, or extrusion equipment. Viscosity results are supported by field experience. Earlier versions of low VOC adhesives proved difficult to apply, and achieve the desired interply usage, in the field. Commercially available, and successfully performing, adhesives "B", "C", and "D" evaluated for this paper are a testament to recent improvements in low VOC adhesive formulation.

Sheet Softness Using a Type O Durometer

Three distinct groupings of softness can be drawn from the data. See Charts 3, 4, and 9: 2002. The same SBS sheet materials were prepared using four different liquid adhesives, torch, mopping asphalt, and self-adhesive. In order of increasing sheet softening effect, they can be ordered as follows:

- Non-solvent application methods (torch, mop, or self-adhesive).
- Solvent-free adhesive "E"
- Low VOC adhesives "B, C and D" ($\leq$ 250 g/L) gave a range of results.
- High VOC adhesive "A" (> 350 g/L).

This sheet softening condition is temporary and the membrane returns to its "normal" state after some time on the rooftop, usually several weeks to a few months depending on the drying conditions.

Peel Strength and Tensile Bond Strength

Two separate issues were evaluated. The first was the "green" strength within the first few days of application of cold adhesive. The second was the ultimate bond strength of various attachment methods when tested unaged and conditioned for 30 and 60 days at 80°C (176°F). Previous work included data with conditioning up to 90 days at 80°C (176°F). Experience has shown a reasonable correlation to the above conditions as follows:[8]

- 30 days is equivalent to approximately 10 years in the field.
- 60 days is equivalent to approximately 20 years in the field.
- 90 days is equivalent to approximately 30 years in the field.

This is of course dependent on many variables such as geographic location of the building, building design and use, rooftop construction, etc.

The data from 2002 combined with the 2007 data shows that, as discussed in the body of the document, that heat welding maintains the best bond strength due to the fusion of two sheets into one. Cold adhesives fair very well over the long-term aging as well. See Charts 5, 6, 7, 8, and 10: 2002. Oxidized mopping asphalt embrittles and steadily loses bond strength over time. The 2002 data also shows a distinct difference in two different sources of oxidized mopping asphalt.

Cyclic Joint Displacement (Cyclic Fatigue)

This data is a good overall indicator of long-term performance, and shows that solvent-based adhesives and heat welding are far superior in maintaining their bond integrity over time when compared with oxidized mopping asphalt.

CONCLUSIONS/RECOMMENDATIONS

Whether by open flame torches, enclosed flame or electric welding devices, heat welded multi-ply modified bitumen applications result in a truly monolithic membrane. Modified bitumen sheets applied with cold adhesive become effectively monolithic, and perform accordingly. This can be demonstrated simply by trying to separate cured, cold applied modified bitumen plies after conditioning in a freezer. Core cuts of modified bitumen sheets bonded with Type III or IV asphalt can be easily separated by hand at temperatures approaching 0^{o}C (32°F). Most cold adhesive applied membranes, however, cannot be separated at temperatures approaching -40°C (-40^{o}F).

Because of this tenacious interply bond strength, SBS membranes applied with cold adhesive or by torching/heat welding exhibit superior fatigue resistance, coefficient of expansion, bond strength, and rooftop performance as compared to oxidized bitumen applied membranes. The tensile bond strength results at both 23 and 50°C, Charts 5 and 6, reveal the excellent short-term uplift resistance of SBS sheets installed with cold adhesives.

Long-term interply performance was also addressed. Chart 12: 2002, illustrates the Cyclic Joint Displacement results of identical two ply SBS, glass reinforced membranes bonded with different interply materials: cold adhesive, torch, and two ASTM D 312 asphalts as shown in Chart 8: 2002. The membranes were tested before aging, and after the heat aging equivalent of 20 and 30 years of field exposure.[3] As mentioned earlier, this test is typically terminated after 500 cycles, but the cold adhesive and torch applied membranes were taken to 1500 cycles without failure. Neither membrane rupture nor interply disbonding was observed.

The combined data from self-adhesive membrane testing shows that it remains prudent to be cautious when specifying, selecting, and installing self-adhesive modified bitumen systems.

Based on the findings in this study, there have been significant advancements with low VOC and solvent-free adhesive formulations. Better long-term performance, or life-cycle, should be expected from properly formulated SBS membrane systems installed with high quality, compatible cold adhesive or with torching/heat welding as compared with hot bitumen applications.

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Illustration 1

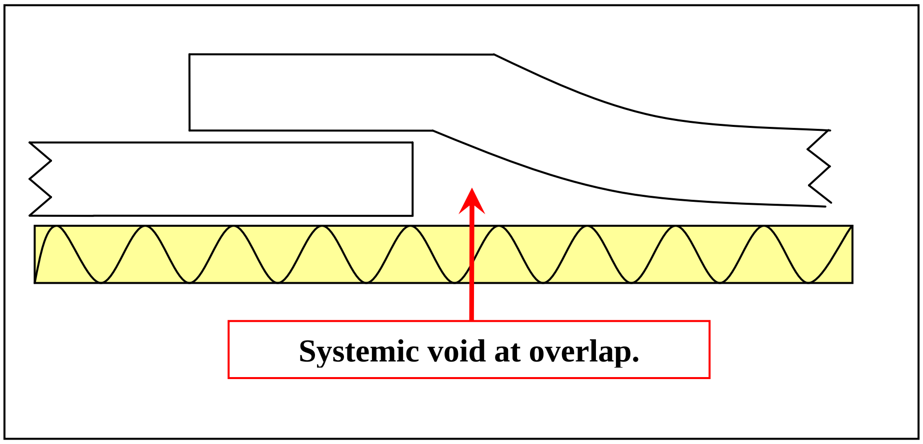


Illustration 2

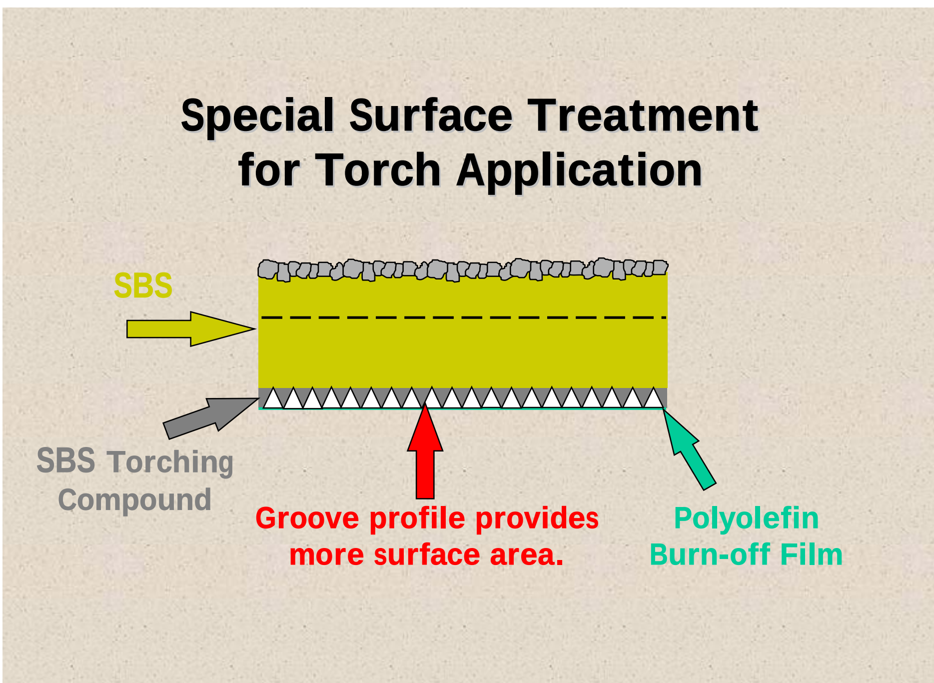


Chart 1

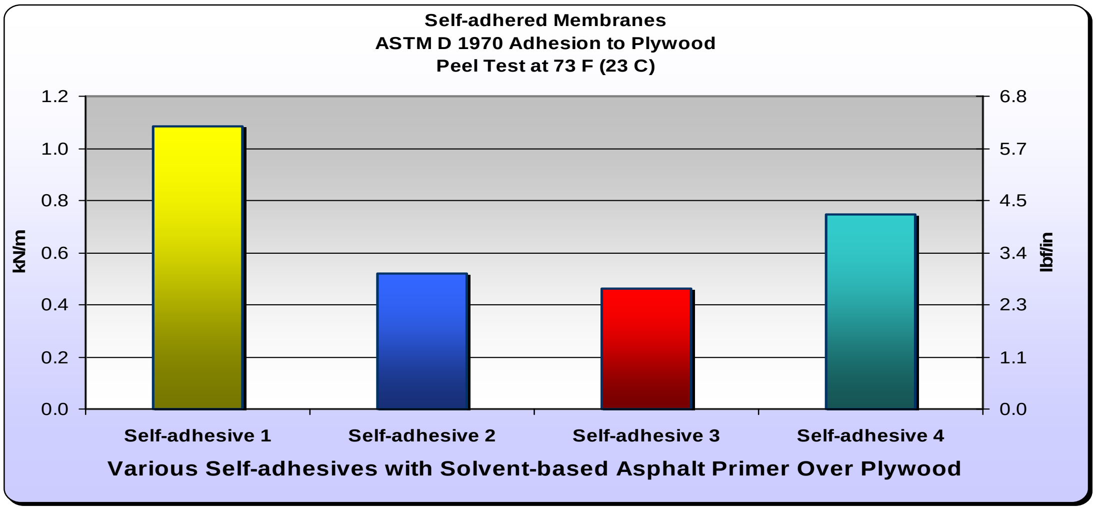


Chart 2

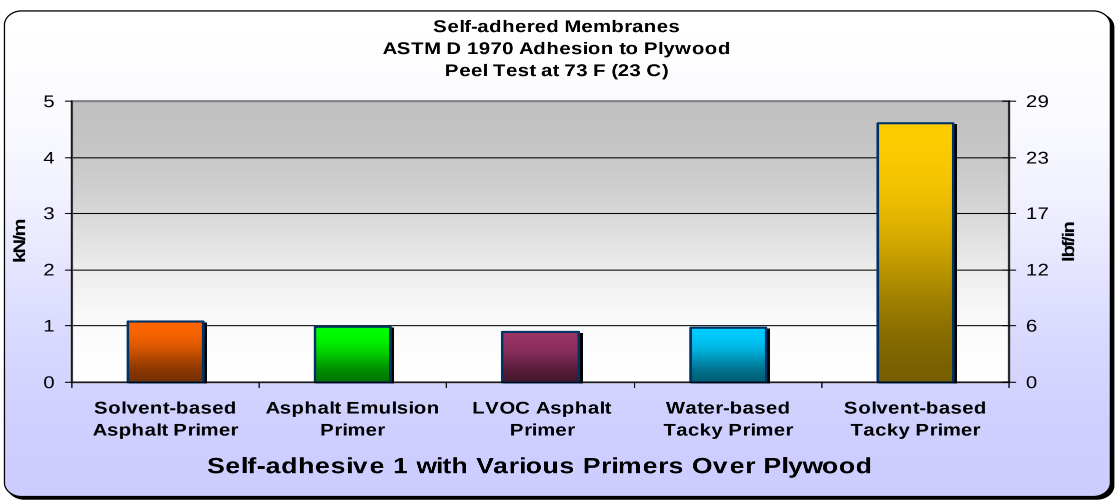


Chart 3

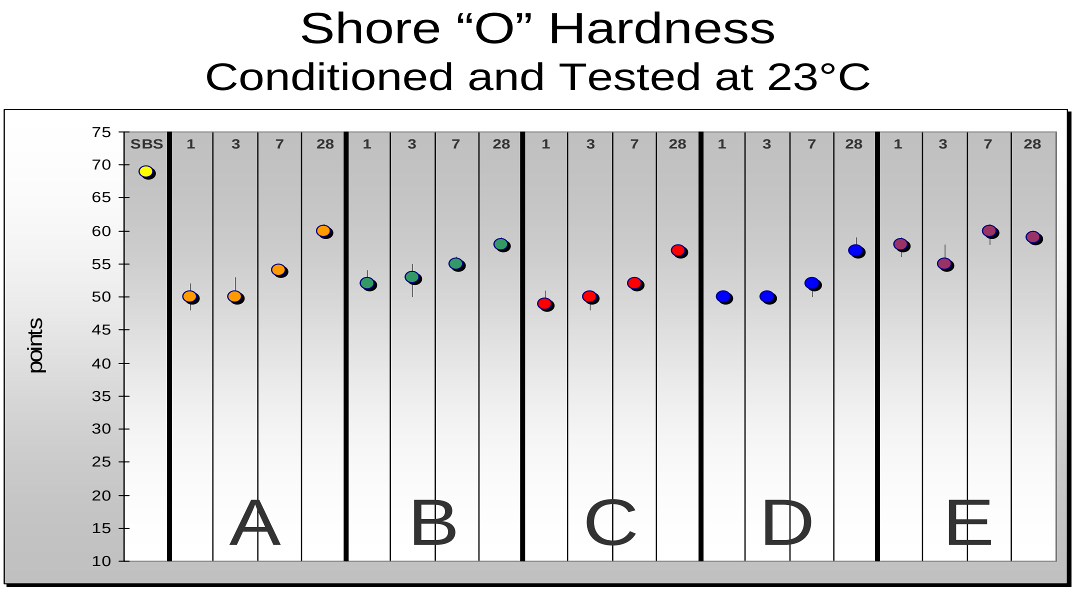
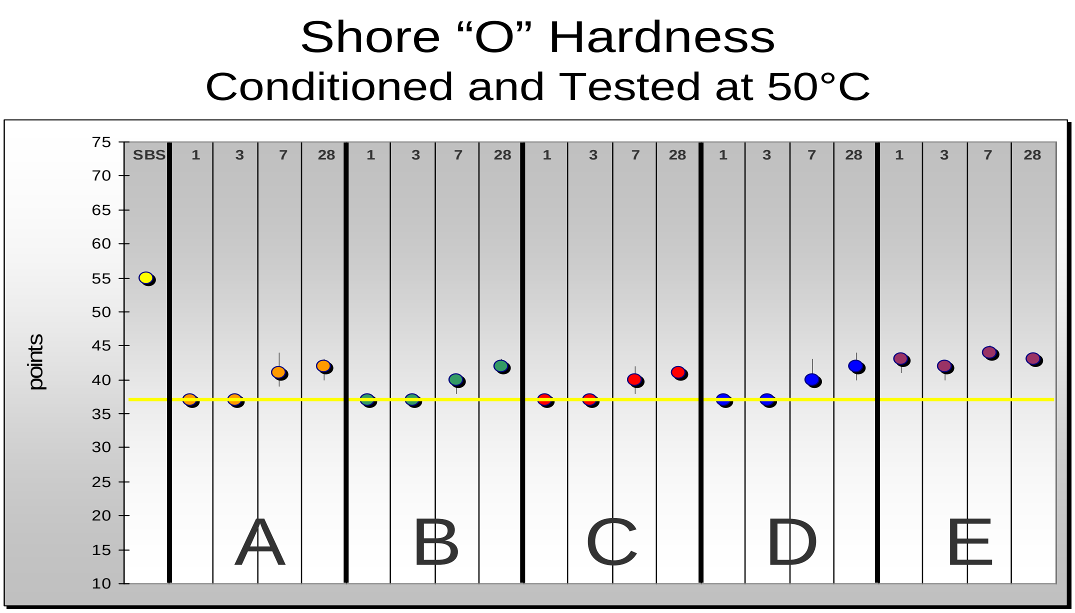
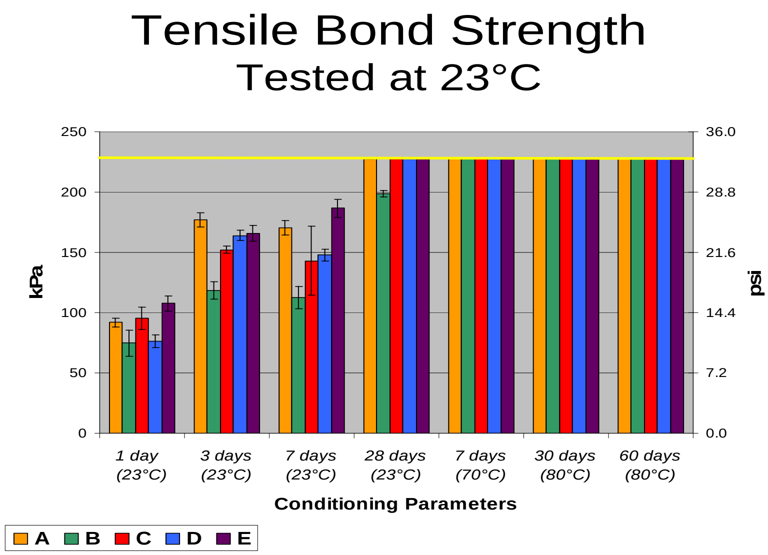


Chart 4



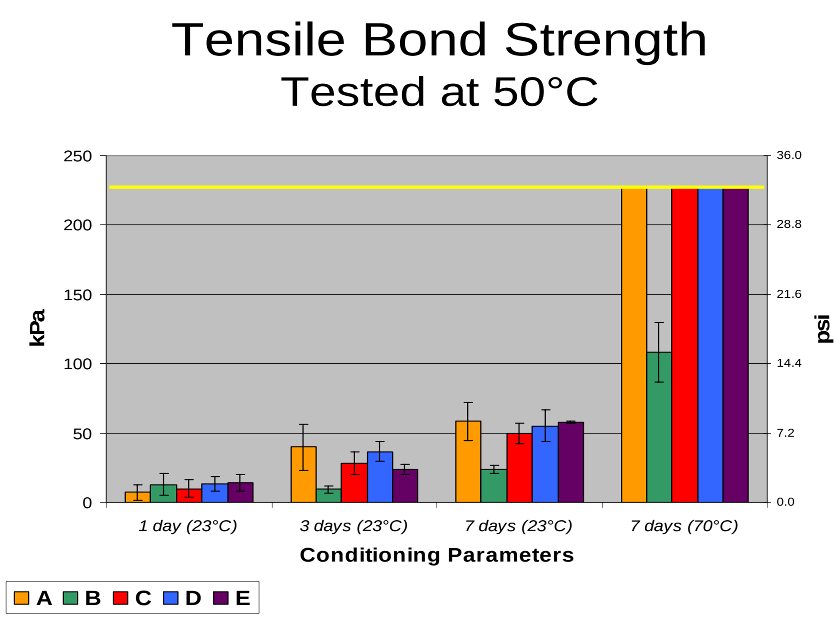
The yellow line indicates where the durometer head impacted the reinforcement in the bitumen membrane.

Chart 5



The yellow line indicates the load limit of the tensile machine.

Chart 6



The yellow line indicates the maximum limit of the tensile machine.

Chart 7

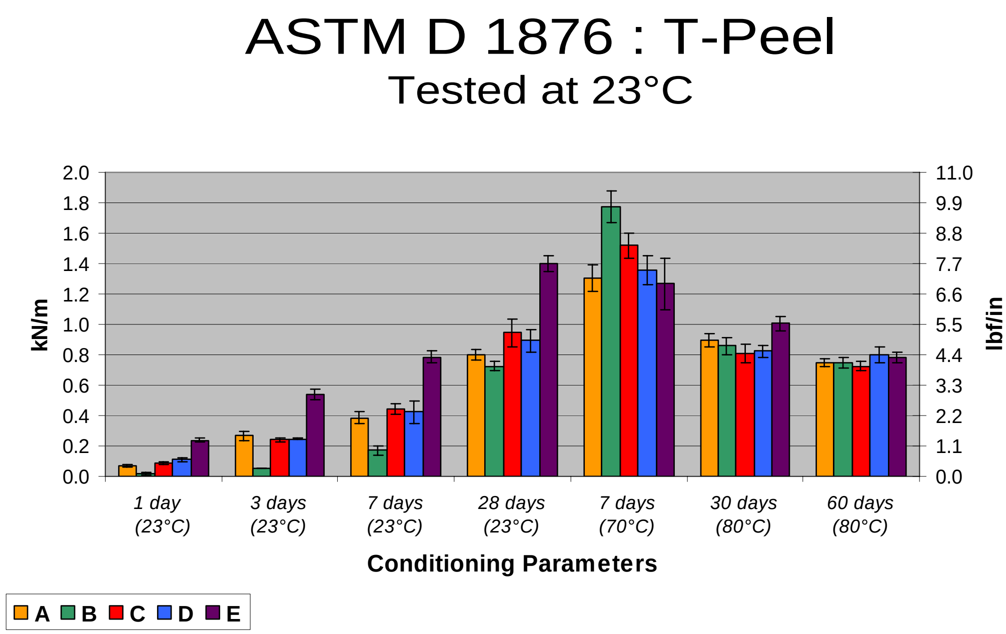


Chart 8

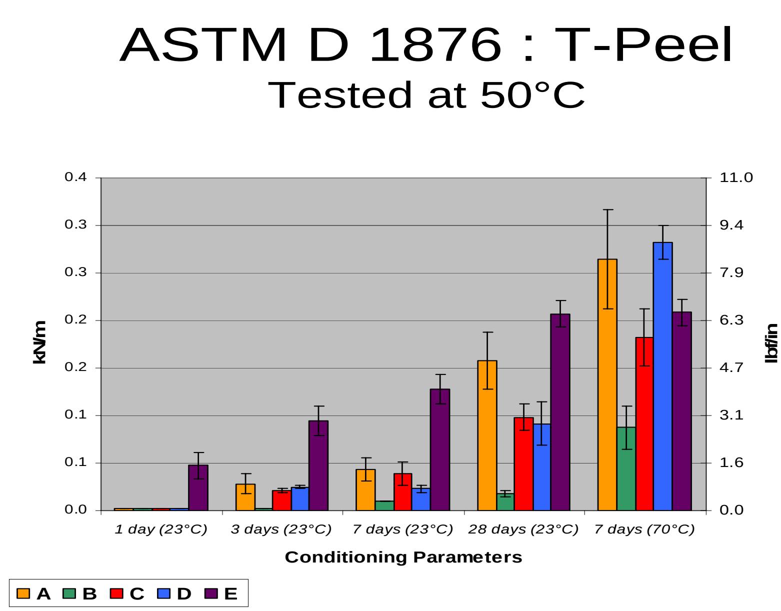


Chart 9: 2002

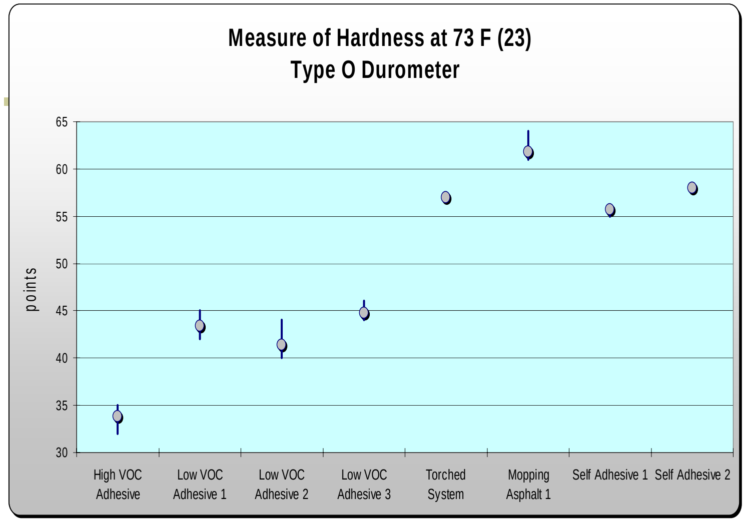


Chart 10: 2002

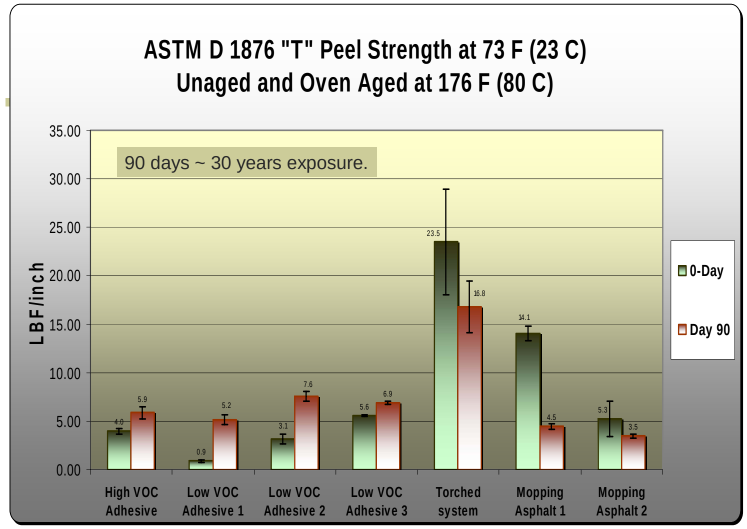


Chart 11: 2002

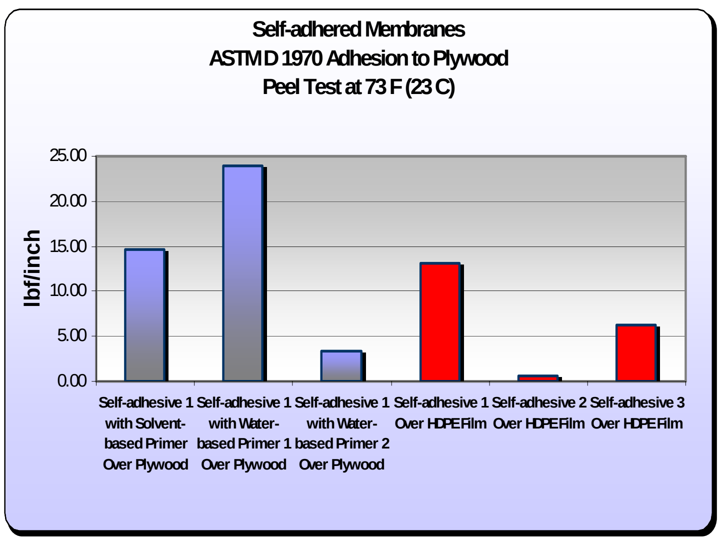
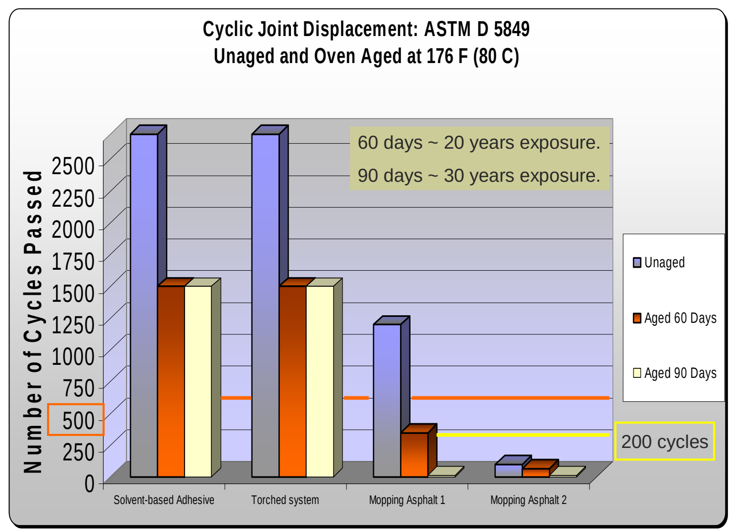


Chart 12: 2002



Charts on this page were presented in the proceedings of NRCA/IWA in 2002.