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PROPERTIES AND PERFORMANCE OF ROOF COVERINGS

R.M. Paroli, O. Dutt, C. Frégeau

Introduction

Roofs used to be simple. The structure had to be sufficiently sloped to allow water to run off. The material could have included asphalt but it generally contained natural fibres which had some binder mixed in to hold it all together. There were few materials and mixtures. Putting a roof together was labour intensive but labour was inexpensive.

Today, millions of square meters of residential and non-residential roofs are covered with water shedding or weatherproofing assemblies. The 1995 North American roofing market was approximately $22 billion Canadian ($18 billion in the US [1] and $4 billion in Canada). A roof assembly contains a roof system over a roof deck. The roof system is defined as having the elements which cover, protect and insulate the roof surface of a structure against the external environment. Roof systems vary from the traditional types (e.g., shingles for sloping roofs and built-up roofing (BUR) for flat roofs) to the non-traditional roofing materials (e.g., polymer-based single-ply or modified bitumen). They also vary in the method by which the covering has been put down. The conventional method is to have the covering (e.g., membrane) above the insulation and exposed to the environment. Alternatively, in a protected system, the covering is directly above the deck and be covered with the insulation.

Irrespective of the system, new materials have been introduced as alternatives to the older ones (see Table I). For example, some shingles are made of modified bitumen instead of blown bitumen. Asphalt-saturated organic felt is increasingly being replaced by asphalt-impregnated glass fibre mat in the manufacture of shingles and as felt plies in BUR. In the new systems, more factory prefabrication and less work atop the roof is involved than in the traditional roofs.

According to the 1994 Canadian Roofing Contractors' Association (CRCA) *Project Pinpoint* survey, the three main roof membrane systems (for flat roofs) in Canada (and their market shares) were as follows: BUR (54.7%), polymer-modified bitumen (33.4%) and polymer-based single-ply (10%). In the USA, the 1995 National Roofing Contractors Association (NRCA) *Market* survey showed a different trend. The asphalt-based systems (BUR and polymer-modified bitumen) and the polymer-based systems were almost as popular. The market share for new commercial construction was as follows: BUR (23.5%), modified bitumen (16.9%), single-ply (40.5%) and metal (6%). The reroofing market was BUR (26.8%), modified bitumen (23.2%), single-ply (32.7%) and metal (4.1%).

Some find this choice overwhelming and confusing. People have had many years of experience using BUR but not many years experience with the newer materials. As a result, the knowledge acquired in the past was of little use for explaining the problems being experienced with the new generation of roof systems. Some of the questions being asked are how do the various systems differ, how do the newer systems behave, is there a perfect system?

Table I List of Various Roof Covering Materials

Material Type	Acronym
Built-up Roof	BUR
Modified Bitumen	MB
Styrene-Butadiene-Styrene Modified Bitumen	SBS
Atactic Polypropylene Modified Bitumen	APP
Ethylene-Propylene-Diene Monomer	EPDM
Poly(Vinyl Chloride)	PVC
Thermoplastic Oligomers	TPO/TPE
Polyurethane foam	PUF
Metal	

The objectives of this paper are to: introduce the different types of roof coverings (BUR, polymer-based single-ply membranes, liquid elastomeric membranes, polyurethane foam roofs and metal); discuss the factors concerning the performance of membranes; and, how they are related to standards. In this paper, a roof cover is considered to be a membrane or metal sheet.

Roof Coverings

Asphalt has been used for thousands of year as a waterproofing material. In North America, asphalt has been used for approximately 150 years as a roofing material. More specifically, BUR has been used for over 100 years. It is still the single biggest type of roofing system installed. The new materials introduced as alternatives to BUR are products of different chemical formulations. Although no panacea, they do provide a wide range of options that meet required performance characteristics. The first generation of these materials suffered some set-backs due to lack of design and performance criteria and lack of experience. However, improvements in their compositions, reinforcing, and lap joint techniques have resulted in a second generation of products with better and progressively improved performance characteristics. The development and promotion of new materials were prompted by the following factors:

- The energy crisis of the early 1970's resulted in an increase in the cost of petroleum-based products. The unpredictability of the sources of oil supplies meant that the quality of asphalt was not consistent. This, in turn, affected the quality of roofing materials.
- Energy-induced inflation raised the cost of labour-intensive BUR, thus making the alternatives economically more viable.
- Advances in polymer chemistry and technology resulted in the development of many polymer-based synthetic materials that could be used for roof coverings.
- During the 1960's new structural design principles gave rise to lightweight structures that caused problems for conventional roofing assemblies owing to their increased structural movement.

- Highly insulated roofs and decks with unusual architectural configurations allowed innovative designs of roof systems that only the new materials could meet.
- The aesthetics of roofs in terms of color and pattern presented the architect with attractive alternatives that would complement the architecture of other elements like flooring and carpeting in a building as well as other exterior elements of the building.
- Better corrosion-resistant metals.

As a consequence, literally hundreds of new roofing materials have appeared on the market. Most of them are polymeric in nature. They are reinforced with a variety of woven and non-woven fabrics of synthetic and glass fibres.

Polymers

Polymers are large molecules containing many smaller building blocks. A polymer or a macromolecule is made up of many (*poly*) molecules (*mers*) or monomers linked together like wagons in a train, for example poly(vinyl chloride), polyethylene, etc. Figure 1 shows the polymerization of vinyl chloride (VC) which represents some 500 to 2000 molecules of VC linked together to make a giant molecule of commercial PVC. Monomers may have the same or different chemical compositions.

Elastomers are a group of polymers that stretch under low stress to at least twice their original length and recover after the removal of the stress. The formation of elastomers depends on the system. For example, EPDM is formed by adding sulfur to the mixture of ethylene, propylene and diene monomer. The sulfur forms linkages between the polymer molecules. This process is known as vulcanization.

Similarly, esters constitute a family of chemicals whose macromolecules are known as polyesters that are used in synthetic fibres, filaments, threads, fabrics, etc. (Their use in reinforcing roofing sheets and membranes is discussed later). Polyurethanes include rigid, semi-rigid, flexible and integral skin foams used in interiors of automobiles and many everyday products.

What are the cover types?

In addition to BUR there are many different types of roof covers. Most are prefabricated sheets or liquid applied materials which upon curing form waterproof sheets or closed cell foams. They are made from a wide variety of synthetic materials (polymers) with various chemical compositions and additives. In some cases, natural materials such as bitumen, organic fibres, etc. are compounded with them.

A brief generic list of roofing membranes is given in Table I. In each type there is a long and growing list of products. No two products are identical even if they consist of the same predominant polymer. A manufacturer may have a number of different products: unreinforced or reinforced with different fabrics, for protected or exposed application, with different seaming techniques and different attachment methods, different colours, etc.

The terms sheet and membrane tend to be interchangeable. A membrane refers to the finished built-up waterproofing layer comprising one or more prefabricated sheets. As such, a sheet becomes a membrane in a single-ply application while a modified bituminous membrane may have two sheets, base and cap. Most of these membranes are composed of mastic, which is the waterproofing component and reinforcing fabrics, which give the membranes the desired physical properties.

What are reinforcements?

Conventional roofing felts are made of asphalt impregnated organic fibres. They act as binders and as reinforcement in the waterproofing component for BUR. In recent years non-woven fabrics have made significant inroads in roofing, in addition to many other fields, such as geotextile and medical fields.

Most of the reinforcements used in roofing are woven fabrics or mats and scrims of non-woven glass fibres and synthetic fibres. They are placed within the body of the membrane. In some cases, a light weight reinforcing mesh is incorporated to act as a carrier during manufacture. Some exposed modified bituminous membranes without granule surfacing have a light glass mat embedded in the top surface to make it crack resistant. The main requirements for the reinforcing fabrics include tensile strength, high initial elastic modulus, tear strength, puncture resistance, flexural stiffness, absorption and fatigue resistance. These and other properties such as dimensional stability are required during the manufacture of the membrane as well as during the performance in the field. The tensile strength and elongation properties can be varied for the desired design requirements. A number of reinforced single-ply sheets were tested for load and elongation at break. The results show variations. Similarly, samples of modified bituminous membranes were tensile tested. Figure 2 shows the differences in their load-elongation pattern. The reinforcements play a very important role in the performance of membranes.

Performance considerations of roofing membranes

Performance means the actual functioning of a building system or element in service. Performance or durability is generally related to the fulfillment of the user's requirements and the desired attributes of materials. Obviously, it is considered the most important factor. Every roof cover, irrespective of the material or the manufacturer, must be capable of doing the following:

- Remain waterproof.
- Withstand all weather factors (such as wind, rain, snow, hail, solar radiation, temperature extremes, and thermal shocks) during its intended service life.
- Resist various stresses from internal or external causes during manufacture, application and service.

It may be appropriate to define some of the terms related to the performance of building materials or components in general.

- Performance requirement is a qualitative statement describing what the system or element is to accomplish.

- Performance criterion is a quantitative aspect of the acceptable or adequate performance level.
- *Characterization* method means a method for evaluating the compliance with performance criteria.

It should be noted that requirement and criterion are interchangeable and, to some it implies both, i.e., the qualitative aspect is implicit in the statement of the quantitative aspects. The selection of a roof cover, like any other building component, must be based on its ability to meet the performance requirements for proper functioning throughout its life.

Performance requirements

The performance of roofs, as mentioned above, is related to numerous variables concerning weather factors and stresses. Other variables are the chemical composition of materials, the quality control of the constituent materials and products during manufacture, storage, transportation, installation and, of course, maintenance. Most of these conditions vary from one situation to another, so that a large number of performance requirements and criteria are identifiable.

In this paper, only the roof covers are discussed, although other components within the roofing system, e.g., the structural deck or board insulation, have an important influence on the overall performance.

One way to predict the performance of a membrane is to identify the physical, chemical and mechanical properties essential for its performance and to quantify them either arbitrarily on the basis of experience or by testing many products in the same generic class. These values constitute the performance criteria for the specific class of product tests. These criteria may be projected with or without modifications to other generic types of membranes. Similar requirements can be developed for a specific product if desired. Quantification of the requirements can be accomplished by comparison or experience with other products.

Table II lists the requirements for roofing membranes subjected to various stresses and strains in different stages of their life. Some of the requirements and common tests that are relevant to field performance are discussed here.

- *Tensile strength, elongation and strain energy and initial modulus.* These properties determine the ability of membranes to repeatedly withstand stresses imposed on them at joints and other places of concentrated movement as well as from shrinkage due to low temperature or membrane creep. The minimum strength requirement also applies to the weakest direction since some membranes exhibit anisotropic behaviour. Since strength and elongation properties vary inversely, i.e. high strength membranes have low elongation and vice versa, the strain energy provides a better measure of the combined properties. Where cyclic loads are involved, as in the case of wind uplift pressure on mechanically fastened roofs, the modulus helps in the design of a fastening system for the load within elastic limits. Some tensile test results are given in Table III that show variations in different products. In general, the elongation varies between 20 and 500% while the strength varies from 10 to **50?** kN/m. Note that unreinforced membranes have very low initial modulus.

- *Lap joint integrity.* As prefabricated membranes have to be joined on site, the lap joint becomes the weakest link because there is no continuity of the reinforcing medium. The lap joint strength is solely dependent on the cohesivity of the joining matrix. In addition, any voids left in the joint tend to blister and weaken the joint in its adhesive strength. Joint integrity is assessed by the pull, peel, shear-peel or adhesion strength of the joint. Even if the strength is adequate, closely scattered voids can still promote water leakage. The lap joint test method needs review in this aspect.

- *Crack bridging ability.* Many shrinkage cracks are present in the concrete roof decks. These cracks, which may be up to 3 mm wide, open and close cyclically with structural movements and thermal variations. A roofing membrane adhered to the substrate at those locations must be capable of bridging the gap. It is difficult for a very well-adhered membrane to provide this capability because the percentage of elongation is very high. The crack-bridging test is applicable to both sheet and liquid-applied materials. For liquid-applied materials, this test is crucial; the results are related to the materials' adhesion property.

- *Tear resistance.* Initiation and propagation of a tear exists where an "oblique" stress occurs along the edges of the membrane, producing a torsional effect. This effect occurs due to an oblique pull at the rollers during manufacture and construction. It also occurs at the points of stress concentration along the edges due to structural movements and to pulls on the sheet during application. This property is important during installation with mechanical fasteners and in being able to support regular traffic which could lead to mechanical damage.

- *Heat aging.* Research and practical experience with the degradation of roofing membranes over a number of years have shown that heat from the sun is one of the most potent factors that affects durability. The heat aging test simulates the accelerated effect of solar heat that changes many properties. The results are compared with those of unexposed material to establish potential durability.

- *Granule embedment.* The exposure of bituminous surfaces to weather elements such as air, moisture, heat and ultraviolet (UV) radiation causes degradation of the bitumens that leads to the loss of adhesion of the protective granules or gravel. The embedment property is thus vital to the durability of the bituminous materials.

- *Static puncture resistance.* The puncture resistance test assesses the ability of a roofing membrane to resist any job-site damage caused by a rough or irregular substrate, traffic during construction or service, or a single human foot on a heated membrane during installation. High puncture resistance is needed for plaza decks.

- *Dynamic puncture resistance.* This is tested with a falling load with an indentor tip to determine if the membrane is damaged to such an extent as to lose waterproofness. It simulates impact from falling objects (e.g., a workman's tool, hail, foot traffic).

- *Dimensional stability.* This important property estimates the dimensional change due to exposure to elevated temperatures, relaxation, loss of volatile components and incompatibility of materials. Dimensionally unstable materials can cause so much shrinkage as to pull the membrane off the flashing or to cause expansion resulting in wrinkles and subsequent failure due to cracking.

- *Permeability.* This property is related to the water vapour transmission (WVT) or permeation. When the substrate is wet the membrane lets the water vapour pass through to dry out the underneath. The rate of WVT is related to vapour barrier in the system and affects the roof assembly design.

In general, the service life of a product is difficult to assess and measure. However, the above requirements or properties must be quantified to establish performance criteria thus allowing the user to evaluate a product. This leads to the development of test methods for evaluating materials that must meet the established criteria and satisfy certain requirements. These results indicate how the material should perform on the roof. In some products, there may be more than one grade. Since the criteria are generally more stringent for the higher grade, a longer service life may be expected.

Regarding the testing methods for these properties, each standard writing organization of each country develops standard requirements which will meet the environmental conditions and the preferred materials. Once the study of a material has come to this stage, the information can be used to develop a standard for the generic type of material.

Thermal Analysis - A New Way of Evaluating Roof Membranes

As mentioned above, the choice of roofing materials is quite varied, ranging from asphalt-based or modified-asphalt (APP and SBS) to polymer-based materials such as TPO, PVC and EPDM. This variety motivated the international roofing industry to shift towards using both engineering and chemical principles in solving roofing problems. In 1988, a joint CIB/RILEM international roofing committee was established to investigate the applications of thermal analysis in the characterization of roofing membranes. These techniques, in conjunction with, the traditional engineering techniques, provide insight into the performance of roofing membranes.

Thermal analysis, until recently, was not widely used in the roofing industry. It is now starting to gain popularity.[2-21] Thermoanalytical techniques can be used to monitor a wide array of material characteristics. Some of the applications include enthalpy, weight-loss, thermal stability, coefficient of thermal expansion(CTE) and the glass transition temperature (T_g). Thus, these techniques can play a role in the decision process for selecting roofing materials. For example, the T_g is an important characteristic that should be considered for the cold temperature performance of roofing membranes Below T_g, the material will be rigid and hard. Yet, above T_g the material will be flexible. Generally, the strength of polymeric materials above the glass transition temperature is lower then the strength below T_g. Other properties that vary with T_g are the CTE and heat capacity.[22-26]

There are four main thermoanalytical techniques that are commonly used to determine and monitor the changes in a roofing membrane. They are thermogravimetry (TG), differential scanning calorimetry (DSC), thermomechanical analysis (TMA) and dynamic mechanical analysis (DMA).

- *TG*. Thermogravimetry measures the change in mass of a material as a function of time at a determined temperature (i.e., isothermal mode) or over a temperature range using a predetermined heating rate. Essentially, a TG consists of a microbalance surrounded by a furnace. A computer records any mass gains or losses. This technique is very useful in monitoring heat stability and loss of components (e.g., oils, plasticizers or polymers).

- *DSC* is widely used in providing valuable information on chemical and physical properties of materials. (This technique is similar to another technique Differential Thermal Analysis or DTA.) The DSC technique measures the amount of energy (or heat) absorbed or released as the material is heated, cooled or held at an isothermal temperature. A DSC thermal curve shows the amount of heat evolved or absorbed as a function of temperature or time. This technique yields thermodynamic data such as enthalpy and specific heat.

  The shape and appearance of DSC curves can give a clue as to the type of transition taking place. Generally, first-order transitions (e.g., melting) give distinct peaks. These peaks can be integrated and a value for enthalpy (ΔH) can be determined. Second order transitions (such as the glass transition) give rise to a step-wise increase in heat capacity which yields a step change in baseline slope. In the case of heavily plasticized materials (e.g., roofing samples) a broad transition is obtained and the step change is difficult to detect.

  The glass-transition temperature, T_g, may be determined by taking the middle of the change in baseline (half-height method). This is facilitated by using the first derivative of the heat-flow signal. T_g values obtained by DSC are generally different from those obtained by dynamic techniques such as DMA since DSC is a static technique.

- *DMA*.[27-31] The DMA technique measures the stress-strain relationship for a viscoelastic material. The storage modulus, E', is a measure of stiffness. The loss modulus, E", is associated with loss of energy as heat due to the deformation of the material. The ratio E"/E' yields the loss tangent or damping factor ($\tan\delta$) which is the ratio of energy lost per cycle to the maximum energy stored and therefore recovered, per cycle.

  A typical dynamic mechanical analysis curve shows either E', E" or $\tan\delta$ plotted as a function of time or temperature. In general, the most intense peak observed for either E" or $\tan\delta$ in conjunction with a relatively pronounced drop in E' corresponds to the glass transition.

  Care should be taken when reporting the glass-transition temperature obtained by DMA. The transition temperature determined by DMA is heating-rate and frequency dependent. Thus, heating rate, frequency and the mechanical/rheological property (E', E" or $\tan\delta$) used to determine the T_g must be specified. It has been found that the E" peak maximum at 1 Hz corresponded closely with the T_g obtained from volume-temperature measurements.[20]

- *TMA.*[28,32] TMA, as defined by ASTM E473-85, is a method for measuring the deformation of a material under a constant load as a function of temperature while the material is under a controlled temperature program. The measuring system consists of a linear voltage differential transformer (LVDT) connected to the appropriate probe. Measurements can be done in compression, expansion, penetration, flexure or in tension mode. It is this variety of probes which allows for the measurement on samples of different configurations. The dimensional change of a sample with an applied force is measured as a function of time or temperature. The plot of expansion (or contraction) vs. temperature (or time) can be used to obtain T_g, the coefficient of thermal expansion (CTE), softening temperature and Young's modulus. The slope of the curve of length vs. temperature divided by the length yields the coefficient of linear thermal expansion.

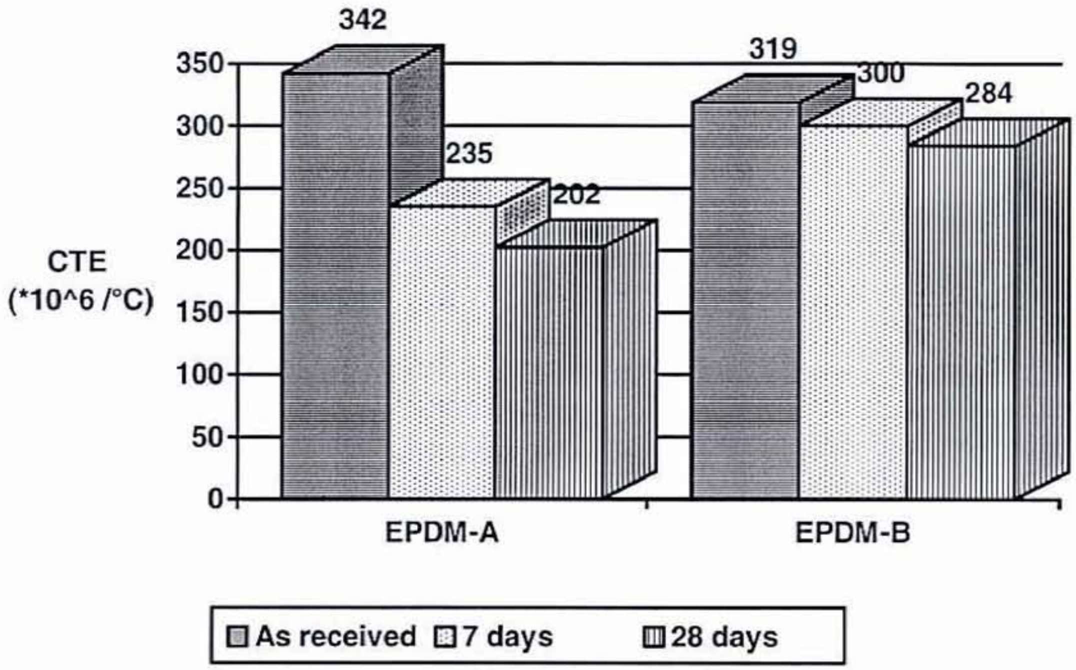
Figures 1 and 2 contain the derivative weight loss (DTG) as a function of temperature of two EPDM roofing membranes. These EPDM membranes had been heat-aged at 100 °C for up to 28 days. It is quite apparent from these curves that one sample (Fig. 1) is more stable then the other (Fig. 2). The observed weight loss (Fig. 2) between 200 °C and 400 °C is due to loss of oils. This loss, significantly affected the in-service performance of this membrane, e.g., severe shrinkage was observed. It is interesting to note that this membrane is no longer available on the market.

A similar experiment was carried out on some PVC membranes. The results are shown in Figures 3 and 4. As can be seen the differences between the two are more subtle than in the case of the EPDM membranes. The sample shown in Figure 4 has actually lost of 4% of its original weight while the one in Figure 3 has not lost any weight.

The results obtained by oscillating DSC on some single-ply membranes are shown in Figures 5-8. It has been found that it is generally difficult to measure the T_g using conventional DSC. However, this was not the case using oscillating DSC. The deconvoluted curves are very similar to what would be obtained by conventional DSC. The Cp curve allows for an easy separation of the T_g component from the rest of the curve. Thus, one can more easily determine if the changes in the baseline can be attributed to the T_g.

DMA curves showing E" results are shown in Figures 9 to 12. Once again, one can clearly discern between a thermally stable membrane and an unstable one. In the case of the EPDM, it is obvious that the peak maximum shown in Figure 9 is not significantly changing, even after being exposed for 28 days at 100 °C. This is definitely not the case for the EPDM sample shown in Figure 10. This sample has a T_g which shifts from approximately -70 °C in the as received mode to -40 °C after 28 days at 100 °C. Similar observations are recorded for PVC samples. Figure 11 contains the E" curve for a PVC sample exposed to 100 °C for up to 28 days. As can be seen, the T_g (approximately -35 °C) does not appear to change. The data for another PVC sample is shown in Figure 12. There it is quite obvious that the T_g has shifted significantly. Changes in T_g can be attributed to various factors (loss of oils or plasticizers, crosslinking, etc.). Since below the T_g the membrane is stiff, DMA allows the membrane manufacturer/user to determine some low-temperature behaviour of these materials.

A typical TMA curve for an EPDM membrane is shown in Figure 13. From such a curve, one can obtain the coefficient of thermal expansion (CTE) and determine the glass-transition temperature. A plot of CTE vs. heat-aging days (Fig. 14) clearly demonstrates how stable one membrane is vs. the other.



Performance and materials standards

The word standard is synonymous with quality. By definition a standard is something that is established by an authority, custom or general consent as a model to be followed. It also means a definite level or degree of quality that is proper and adequate for a specific purpose. Standards are desirable for product acceptance in the market. They assure buyers of quality and protect producers and distributors from poor quality product competition.

In today's industry, which includes manufacturing, sales, construction and maintenance, standardization is most essential. It is estimated that close to one million standards exist in the world and that some 50,000 standards are used each day in various activities around the world. In the construction industry they are used for the procurement of materials, design verifications, installation procedures, manufacturing, quality control, etc. When many firms are involved in a construction activity, standards become paramount even for communication.

The development of a standard involves the representation of all of users, producers and general interest members. As Canadian and other standards are generally voluntary and based on consensus, all opposing views on the contents can be expressed during development. However, the process starts only after the need for a standard has been established through investigations of its feasibility, practicality and desirability. Appropriate test methods to evaluate the various physical, chemical and mechanical properties are developed. An interlaboratory testing program is then designed to evaluate the material and proposed test methods. The final step is the writing and balloting of the standard. It is only after close examination of every statement in the standard that it is considered an acceptable document.

In Canada, roofing standards are the responsibility of the Canadian Standard Association (CSA) and the Canadian General Standards Board (CGSB). Both organizations are part of the National Standards System, as shown in Figure 4. CSA is concerned with bituminous roofing materials (e.g., shingles, roofing felt, roll roofing, etc.) and tiles. CGSB deals with modified bitumens, tars, cutbacks, emulsions and polymeric roofing materials, etc.

Unless referenced in regulations, Canadian standards are considered voluntary. These standards are referenced by the National Master Specification and utilized by government departments such as Public Works and Government Services Canada and the Department of National Defence when specifying materials for contracts. Other groups, such as the Canadian Construction Materials Centre (CCMC), utilize these standards to evaluate products for equivalency to roofing requirements in the National Building Code of Canada.

Although there are no standards for BUR as such, there are standards for different felts, bitumens and surfacing materials. Trade organizations like the Canadian Roofing Contractors Association (CRCA) publish specifications detailing construction methods, which they update regularly.

Standard requirements for three prefabricated membranes are given in Table IV and for two of the liquid-applied membranes in Table V. The third one, SPF (Table V), is basically an insulating material, but can also be used for waterproof. These requirements are representative of the variety of criteria, some of which are performance-oriented while others are considered material properties.

There are always questions as to the quantities related to the requirements and test methods. For example, a material having 10 MPa strength does not imply that it will last twice as long as a 5 MPa material. In the PVC standard, the requirements for a reinforced sheet is different from that of an unreinforced one. The reinforcement provides strength to the matrix and should cracking occur, the damage would be more localized. It is for this reason, that the elongation at break for unreinforced PVC membranes is 250% while for a reinforced membrane it is set at 15%.

The test method for the watertightness test is such that any material would pass unless there happens to be a pinhole or other defect at the test spot. In the case of rubberized asphalt, the toughness ratio may be useful as an ad hoc test for comparison with similar products, but it does not have scientific relevance to the field performance.

Accredited Standards Writing Organizations (SWO)

- Bureau de Normalization du Québec (BNQ)
- Canadian Gas Association (CGA)
- Canadian General Standards Board (CGSB)*
- Canadian Standards Association (CSA)*

	• Underwriters Laboratories of Canada (ULC)*
Accredited Certification Organizations	• Canadian Gas Association (CGA) • Council of Forest Industries, B.C. (COFI) • Canadian Standards Association (CSA) • Underwriters Laboratories of Canada (ULC) • Warnock Hersey Professional Services (WHPS)
Accredited Testing Organizations	Over 50 in many different areas. Those testing roofing materials: • Technical Service Laboratories, Div. Of Burgener • Technical Enterprises Ltd., Mississauga, ON • Quality Assurance Product Test. Lab., Fiberglas Canada Inc., Sarnia, ON • Techmat (1983) Inc., Jonquiere, QC • Warnock Hersey Professional Services Ltd., Mississauga, ON
Associate Committees (Organizations in Liaison)	• For the National Building Code (ACNBC) • For the National Fire Code (ACNFC)

* Deal with roofing standards.

Figure 4 National Standards System of Canada

Some application standards are unclear in many aspects. They should emphasize and caution field workers of the problem areas.

Membrane characteristics

Bituminous built-up roofing (BUR)

All of us are familiar with conventional built-up roofing membranes, which have been used successfully since time immemorial (they were even used in the Hanging Gardens of Babylon). At one time, built-up roofing membranes were almost the only membranes used. They still account for a large part of the roofing market. A BUR membrane is traditionally made by using several layers of roofing felts bonded together with hot bitumen and then covered with a waterproof pour coat. Bituminous materials used in BUR include (a) asphalt, obtained in petroleum processing, and (b) a product extracted from coal known as coal-tar pitch (CTP) [also referred to as tar or pitch]. In Canada, CTP is generally not available unless imported. Asphalt used for saturating organic felts is commonly called No. 15 because the earlier types weighed 15 lb/100 ft^2. It is important to note that these two materials are not compatible. Tar is not soluble in paint thinner, whereas asphalt is, imparting an amber colour to the liquid. This and asphalt-impregnated glass fibre felts are used as plies in the construction of BUR. Heated asphalt is mopped on each felt layer to bind them together into the finished multi-ply membrane.

BUR membranes are resistant to wear and puncturing, mainly because of their thickness. But the individual components are generally not very strong (the plies may be paper-based) and of poor quality (the tar or asphalt may contain oil-refining residues). The combination of these materials, however, provides the desired strength.

Since this type of membrane is manufactured on site, quality control must take place while the membrane is being installed. This can only be achieved by continual inspection. The inspector needs a thermometer or other similar device, such as a heat gun to check the temperature of the tar or asphalt as it is being laid down. The inspector must also have a contact hygrometer to test the moisture content of the felt plies. The resulting membrane is thick (±1 cm) and relatively sturdy, but not very flexible at low temperatures. BUR membranes are often covered with crushed gravel, which acts as ballast, protects against UV radiation, and provides resistance to the effects of sudden temperature changes. BUR membranes are generally assembled with five (5) plies to obtain the guarantee of the Canadian Roofing Contractors' Association (CRCA) or some provincial associations such as the Association des maîtres couvreurs du Québec (AMCQ).

Three types (CSA 123.4.M) of asphalt are available in Canada. (i) Type I - softening point: 60 °C, for slightly pitched roofs; (ii) Type II - softening point: 75 °C, for moderately pitched roofs; and, (iii) Type III - softening point: 83 °C, for steep pitched roofs (Type III is currently difficult, if not impossible, to obtain). Using the right type is crucial if one desires to reduce the occurrence of problems such as slippage. In practice, however, slippage is not uncommon, even when the right type of asphalt is used.

Many problems in BUR, like blistering, are related to moisture and air voids in the membrane. The organic felts absorb moisture from improper storage and the lack of protection from rain during installation and as a result lose strength due to wetness. Sometimes moisture is trapped where there are skippings in the mopping of asphalt under the felt. Also, synthetic fibre from rags sometimes get included in the felts during manufacture, resulting in poor asphalt saturation.

BUR membranes, whether made with asphalt or tar, cannot withstand contact with oils, greases or solvents. Eventually, the felt layers will deteriorate, leading to membrane failure. The composition of a traditional BUR membrane can be improved by replacing No. 15 organic felt, which is subject to decay, with the more inert No. 15 glass fibre felt which binds the plies to each other much more effectively. However, glass fibre felts are quite porous and provide good adhesion. Their use in flashing is not recommended. During installation, walking over felt on hot asphalt causes the asphalt to squeeze out, which could result in a void and lack of adhesion in the membrane, a potential source of moisture problems.

A very common source of problems is overheating asphalt. This apparently makes the mopping easy. Overheating the asphalt may lower its softening point. Overheating asphalt has two opposite effects. It hardens the asphalt as it volatilizes the oil. Yet, its equiviscosity tends to decrease to that of an inferior grade (reduces both its softening point and coefficient of linear thermal expansion). The surface causes shrinkage cracks and alligatoring.

Some other problems in BUR include shrinkage of the membrane that pulls flashings away, caused by a lack of adhesion of the roofing system to the deck. Membrane slippage occurs if the softening point of the asphalt is too low with respect to the roof slope, or the amount of interply asphalt is excessive.

Some manufacturers improve the physical properties of BUR membranes by substituting modified bitumen for one or more layers of ordinary oxidized bitumen (asphalt). Builders have begun to improve this system by using modified bitumen for flashing. The materials are compatible, provided the polymer additive is SBS- (styrene-butadiene-styrene) based. This solution sometimes represents a necessary evil, but it is an effective way of improving waterproofing at weak points.

Modified bituminous (MB) sheets

This class of sheets is made from bitumens and modifying polymers (synthetic rubbers or plastic materials), together with fillers and special-property additives. Since the process is basically mixing components, the amount of modifier can be varied according to the required characteristics. The physical properties and softening points of the resulting modified bitumens are far superior to those of the traditional oxidized bitumens. The engineers and chemists who designed these membranes did so with the specific problems of roofing in mind: sudden cooling, resistance to UV rays, dimensional stability, elasticity, permeability and resistance to moisture, puncture, and ozone.

The two most widely used bitumen modifiers are SBS (styrene-butadiene-styrene) and APP (atactic polypropylene). The average SBS content in the formulation is 12-15%. Generally, more SBS means greater low temperature flexibility and fatigue resistance as well as a higher softening point and wider temperature use. There are about a dozen different SBS grades that accentuate one or the other property required for processing and performance of the membranes. APP is a by-product of the manufacture of IPP (isotactic-polypropylene). It comprises 25-35% of the modified compound, its primary function being to improve the mechanical properties of the finished membrane. The APP-modified product has higher strength and lower elongation compared to the SBS-modified type. A small quantity of filler provides rigidity to the compound but large quantities reduce flexibility and adhesion. Consequently, the best products have the least filler.

SBS-modified sheets are used mainly for roofing, because they are flexible at low temperatures. In Canada, APP-modified sheets are used mainly to waterproof foundations, tunnels, as well as in protected membrane roofs.

Table Typical composition of a modified bitumen membrane

Ingredients	% Weight
Asphalt	50
APP or SBS	25-35
Filler	10-20
Oil	5

Proper modification of bitumen results in a product whose performance characteristics are far superior to those of normal bitumen. Various types of reinforcements, particularly glass and polyester composites incorporated in the membrane, provide improved properties. Some have a substrate consisting of a plastic sheet, film or mat. Modified bitumen does not withstand harsh weather much better than unmodified bitumen. For this reason, granules protect the surface from the degrading effect of UV. In some membranes a light glass mat laminated to the surface protects the surface from cracking and acts as a replacement for granules. The number of reinforcing fabrics and their positioning depends on the design of the product. The sheets are up to about 5 mm thick.

In addition to providing membranes whose characteristics and properties have already been determined through testing, this in-plant prefabrication process means that only the installation itself needs to be monitored at the site. Quality control of the materials has already been done at the plant. Overheating or applying the wrong thickness of asphalt is no longer a major concern. If the various rolls of membrane are applied and sealed properly then the specified degree of watertightness will be achieved.

Most modified bitumen membranes are designed to be installed as a two-ply system. The bottom sheet has no special surface and is often thinner and lighter than the top sheet. The top sheet has a special protective surface made of mineral granules or a thin layer of metal. Some manufacturers make the bottom sheet thicker. Since these sheets use thermoplastic bitumen materials, they can be applied in a variety of ways. These membranes are frequently applied by torching (open-flame melting) the underside as the sheet is being unrolled. Others have self-adhesive backing or may be adhered with a mopped-on adhesive. The torching and self-adhesive backing methods offer a considerable advantage in areas where transporting the equipment needed to heat and apply bitumen poses problems. However, using torches on a roof creates greater safety hazards and requires appropriate precautions. As a result, some manufacturers have introduced an electric heat-welding process.

Heat application requires great care because if the temperature is not kept within a certain range, the joints may be defective. The heat method is used to apply modified bitumen sheets mainly when the modifier is atactic polypropylene. If SBS sheets are sanded first, they can be installed with a torch. The strips of plastic tape **must be removed before this is done.** Overheating modified bitumen degrades the mastic and leads to poor adhesion and weak lap joints.

Modified bitumen membranes are usually applied to the substrate, but they can also be applied as an independent system or as a protected membrane system. The adhesive side of the sheets is very sticky and will stick to itself or to the substrate if workers do not take proper precautions after they remove the paper backing that prevents the paper from sticking to itself while it is still rolled up. These sheets will not adhere to surfaces that are dirty, wet, or icy. so it is very important to make sure the substrate is properly prepared. A torch can always be used to do the flashing.

Liquid membranes

There are many different categories of liquid membranes. The two main ones are hot-applied rubberized asphalt and cold-applied chemical compounds. Both use bitumen (asphalt or tar) for waterproofing the systems and organic fibres in rags, cloth or cellulosic felt saturated with bitumen for reinforcing. Mineral materials such as granules and gravel are applied on surfaces to protect bitumens from ultraviolet (UV) radiation.

Hot-applied rubberized asphalt

Hot-applied rubberized asphalts consist of proprietary blends of asphalt, mineral fillers, elastomers (natural, synthetic, or a blend of both), virgin or reclaimed oil and a thermoplastic resin. The compound is melted in a double boiler, then applied hot on the concrete surface using a rubber scraper. The reinforcing material generally consists of a thin ply of fibreglass or polyester, with butyl-rubber strips applied at the angles. It is applied hot in such a manner as to form an impermeable monolithic membrane over the surface to be waterproofed, which may be concrete, gypsum board or wood. Improved versions of this type of system consist of two coats of rubberized asphalt with a polyester mat in between, called the fully reinforced or two-ply system.

Hot-applied liquid membranes are used for protected membrane roof systems, as well as to coat foundations and underground structures such as parking garages. These membranes are horizontally reinforced with polyester and with heat-welded strips of butyl rubber or modified bitumen (SBS-based modified bitumen is generally compatible with rubberized asphalt). Unfortunately, adhesion between the rubberized asphalt and the butyl rubber is not excellent under tension, and problems occur at the points where these two materials are joined.

Table Typical composition of a rubberized asphalt

Ingredient	% Weight
Asphalt	40
Rubber	18
Filler	37
Oil	5

Cold-applied

Cold-applied liquid membranes are typically made up of two components, one of which is a catalyst. This category of material comprises a number of different products in the market. They consist of emulsions and solutions of (a) various resins or elastomers such as polyurethanes, silicones, acrylics, etc., and (b) bitumens and modified bitumens. The material left after the evaporation of volatiles (water or organic solvents) forms the waterproofing layer. Their surface coatings may contain white pigment or aluminum flakes or they may be vinyl films for protection from solar radiation. They are spread or sprayed on surfaces that have been pre-coated with polyurethane foam, or directly on untreated concrete or plywood surfaces. The emulsions cure slowly at low temperatures and they cannot be applied below water's freezing temperature. The solution forms a film much faster under these conditions.

Cold-applied liquid membranes can be applied effectively to steeply pitched surfaces and concrete substrates. They can be applied on top of a layer of high-density polyurethane foam insulation or of other material. When this kind of membrane is applied on top of polyurethane foam, the membrane itself must be carefully maintained to protect the foam underneath. It also requires regular recovering and constant maintenance when water has begun to penetrate under the membrane.

Also, the cutbacks (solutions) and emulsions (water dispersions) of asphalt and coal tar pitch are used in various types of cold applications of BUR. Polyester mats are used as alternatives to conventional felts for plies. The market share of cold-applied BUR's is small. From the point of view of economy and availability, asphalt is more commonly used in this type of roofing product.

Polymeric Sheets

Since World War II there has been a gradual increase in the use of single-ply membranes, made of a variety of polymeric materials. Single-ply polymer roofing membranes have been available in North America since the 1950's. Many new products were introduced to the market such as polychloroprene (CR), chlorosulphonated polyethylene (CSPE), EPDM and PVC. Unfortunately, since these products were different then the traditional asphalt, new installation techniques had to be developed. Many companies were unaware of the critical role that installation technique would play and as a result, many failures occurred. Today, there are much fewer companies involved in the manufacturing of single-ply membranes.

The advantages of such systems include speed of installation and no need for open flames or heated asphalt. However, they must be installed by properly-trained and manufacturer-approved installers. Most single-ply manufacturers claim that their products have a service-life of at least 15 years. The membranes are formulated to resist UV, heat, bacterial attack, etc.

The nomenclature used in the industry for these single-ply systems is based on the main chemical ingredient. (e.g., PVC, EPDM, etc.). This is convenient for discussion purposes but it must be remembered that all of these membranes contain additives which are required to impart the desired properties such as flexibility and weatherability. In general, there are two categories of polymeric sheets: elastomeric and thermoplastic.

One advantage of single-ply membranes is their smooth finish, which makes it harder for ice to adhere to them. Membranes with rougher surfaces may fail in winter because the ice clinging to their surface is shattered by a sudden drop in temperature. Moreover, single-ply membranes have a high vapour permeance (as much as 50 times greater than some asphalt roofing materials) and can therefore be used to build roofing systems that are not subject to condensation in winter. Single-ply membranes are also easy to repair. Tests have shown that when new single-ply material was used to patch a previously installed membrane, the resulting strength was just as great as that or the original material. As regards fire resistance, single-ply membranes can be formulated so as to meet both Factory Mutual and Underwriters Laboratories test standards for Class A and Class I roofs.

The following list is not exhaustive. There are many other types of single-ply membranes, generally composed of uncured, vulcanized or unvulcanized, thermoplastic rubber and generally containing high proportions of PVC. The newer single-ply assemblies could eventually eliminate the need for asphalt on the roof (although this is not expected to happen in the near future). This reduces the logistical problem of raising hot bitumen and gravel to the roofs of high buildings and reduces the weight of the assembly. Single-ply membranes, including any required adhesives or mechanical fasteners, weigh between 2.5 and 7 kg/m². However, ballasted single-ply assemblies do not benefit from any weight advantage as the required ballast adds significant weight, sometimes up to 40 kg/m².

Elastomeric sheets

There are many types of elastomers or synthetic rubbers used in roofing, including EPDM (which is naturally flexible), neoprene, CSPE (also known as Hypalon™), butyl, nitrile, etc. They are compounded with polymers and ingredients such as fillers, anti-degradants, processing oils and processing aids, to impart the required properties. Polymers provide the muscle and fillers provide bones to the materials. Stabilizers (e.g., anti-degradants) improve weathering properties of the membranes. The most commonly-used elastomer in roofing is EPDM. The compound contains 30-50% polymer (ethylene-propylene-diene monomer), 20-30% carbon black and 30-50% extender oil, sulfur, accelerator and antioxidant. Sheets are produced by laminating two plies with or without reinforcing.

Vulcanization is the process of converting a raw rubber to a crosslinked network. This is generally, an irreversible process. The most common method of vulcanization is with the addition of sulphur (and metal oxides) although other cross-linking agents can be used. Chemically, the sulphur forms bridges (or bonds) between the rubber molecules. The end result is increased stiffness, reduced sensitivity to solvent swell as well as other enhanced physical properties.

The non-vulcanized or uncured rubber sheets that are self-curing are gradually cured on the roof by heat from the sun. Once they are cured, their behaviour is similar to that of cured elastomers. If they are not self-curing, they remain uncured and exhibit properties similar to thermoplastics during their service life. In general, elastomeric sheets have good tensile and other mechanical properties and excellent resistance to UV, ozone, many oils, and solvents.

Field seaming of some vulcanized sheets, known to cause some problems, is progressively being improved. Doing the maximum possible seaming in the factory reduces the amount of field seaming and the probability of problems. Some aspects have been discussed above in the section on lap joint integrity. Proper choice of adhesives, care in the preparation of the seam area, skillful application, and adequate curing time could result in a durable joint. It should be noted that work is currently underway at the National Institute of Standards and Technology (NIST) to study the use of tapes instead of liquid adhesives for seaming.

- Butyl rubber

One of the oldest types of single-ply membranes, butyl rubber is produced by copolymerization of isobutylene and isoprene, followed by vulcanization. (Isobutylene and polyisobutylene cannot be vulcanized in their pure form.) Butyl rubber membranes are the forerunner of modern EPDM membranes. At one time, butyl rubber sheets were commonly used to create watertight membranes. This is no longer the case because the joints do not have good long-term performance. Butyl rubber sheets are still used in built-up roofing systems for expansion and control joints and sometimes for base flashing.

- EPDM

According to CGSB 37-GP-52M, EPDM is composed of ethylene, propylene, and diene monomer, forming a synthetic rubber whose properties are actually similar to those of natural rubber.

EPDM was introduced to the market in 1960 as the successor to butyl rubber. Like butyl rubber, EPDM is extremely resistant to ozone. The first attempts to use it in roofing membranes failed, for several reasons. After installation, the material could shrink by as much as 2% (i.e., 2 cm per 100 cm). The glued joints did not stand up well and some manufacturers used oil which was too volatile. But further research yielded superior formulae and production of EPDM and adhesives, resulting in better performance.

The first EPDM roof in Canada was installed on the Sheraton Hotel in Toronto in 1961. By 1970, the oil crisis had made EPDM membranes an attractive alternative to asphalt roofing. (Asphalt, being an oil-refining by-product, was affected when the cost of oil rose from $3 to $30 a barrel. The market price of asphalt went up and its quality went down.) Today, the market for this type of membrane is experiencing vigorous growth. It is widely used in the United States in all large industrial roofing systems. The reason for this is the very low cost of this synthetic rubber.

EPDM membranes are produced by lamination or lapping. In the latter case, pinholes may appear, and two sheets are seamed together to avoid having two pinholes on top of each other. Preferably, joints should be made in the factory, but they can also be made in the field, using self-curing, self-adhesive strips or contact cement. EPDM has yet another desirable property: it remains highly elastic at temperatures as low as -40°C.

EPDM is highly resistant to ozone and ultraviolet rays. It requires some care during installation, because of the self-curing strips or in-seam sealants used to make the joints, and also requires some ongoing maintenance. Its natural colour is black, but it can be painted with latex paint. Five (5) to fifteen (15) year warranties are available.

Table Typical composition of a generic EPDM roofing membrane.

Ingredient	Percent Composition	Function
Polymer	25% - 35%	Imparts elastomeric properties
Carbon Black (for black EPDM) or Titanium Dioxide (for white EPDM)	25% - 40%	Reinforces properties, absorbs UV and acts as filler

Extender Oil, Accelerator, Sulfur and Anti-oxidant, Processing aids, etc.	20% - 25%	Aid processing and reduce cost, promotes proper cure, assist in resisting environmental factors, promotes anti-sticking, and provides smooth surface in calendering

- Polychloroprene (CR)

CR, better known under the trade name Neoprene, consists of hydrocarbon molecules and chlorine atoms. It is the product of the polymerization of chloroprene, or of the copolymerization of chloroprene with various monomers. This membrane is composed of chloroprene which gives the material amazing flexibility. The joints are made using rubber or contact cement.

In its incompletely cured form, CR is used as the main polymer in manufacturing contact cement and sheets used for flashing. Curing is completed after installation, under the effect of heat. Waterproof sheets of fully vulcanized neoprene are also available.

Neoprene is one of the synthetic rubbers that displays the best resistance to petroleum products, solvents, and various ageing agents. Some manufacturers recommend applying a coating of coloured CSPE to CR sheets, both to protect them from UV and for aesthetic reasons. CR sheets usually come in thicknesses of 0.75 to 3 mm; the ones used in roofing are generally 1.5 mm thick.

Thermoplastic sheets

As the name implies, thermoplastic polymers soften when heated and thus can be easily extruded or molded. They are distinguished from thermosets by the fact that there is no cross-linkage or vulcanization of the molecules. Welding together using heat or a solvent is easy and creates new molecular linkages during service life.

- PVC

Poly(vinyl chloride) is one of the most versatile thermoplastics in use today. It is produced by polymerization of vinyl chloride monomer, a gas produced by the reaction of ethylene with oxygen and hydrochloric acid. This reaction produces a chemical bond that is saturated and hence highly inert and almost indestructible. In its basic form, PVC resin is a rigid substance to which plasticizers, stabilizers, and other components must be added to provide the desired properties for the PVC's intended use. PVC is used for a wide variety of products, ranging from automobile seat covers to electrical cable insulation to home siding. All of these products are made of PVC, but they differ in the grade of PVC used and the stabilizers, plasticizers, fungicides, and other substances that are added to it. The basic formula for PVC is now well known throughout the industry.

Its use in roof covering started in the sixties. In a PVC sheet, the compounded plastic is the key element that determines the final characteristic of the product and acts as a binder for the system. The plasticizers impart flexibility to the sheet and improve processing.

Fillers and extenders (such as calcium carbonate) are used primarily to lower the raw material cost of the compound. They also improve processing and affect other mechanical properties, such as the hardness and dimensional stability of the finished product. Stabilizers protect PVC against heat during processing and against ultraviolet radiation during service. Pigments are added to color the plastic material.

Table Typical composition of a generic unreinforced PVC roofing membrane.

Ingredients	% by Weight	Function
PVC resin	50 - 55	Basic material (powder or granular)
Plasticizers	25 - 30	Impart flexibility
Fillers	5 - 10	Increase dimensional stability, and reduce cost
Pigments	0.5 - 1.0	Provide color and UV stability to the PVC compound
Processing oils and biocides	0.5 - 1.0	Improve processing and resistance to biological attack
Stabilizers	2 - 3	Provide resistance to heat and light during manufacture and installation

Note: Based on technical notes and some related patent specifications

PVC sheets are produced by three basic methods, calendering, extruding and coating. There are three types of sheets: unreinforced, lightly reinforced with fibres or fabrics that act as carriers, and reinforced sheets that contain glass and/or polyester fibres or fabrics. Reinforcements may be composed of unwoven polyester or woven or unwoven glass fibres with characteristics similar to those of modified bitumen membranes. Polyester reinforcement is used to increase the membrane's resistance to tearing in the wind. Polyester reinforcement is used mainly for sheets that are going to be fastened mechanically, while fibreglass reinforcements are used for independent installations. Fibreglass reinforcements are used mainly to prevent residual shrinkage. The carrier facilitates manufacturing and adds to the dimensional stability of the sheet. Reinforcement provides tensile and other properties. Generally, unreinforced sheets are produced by calendering or extrusion. Reinforced sheets can be produced by laminating two plies of unreinforced sheet with a layer of reinforcement between them.

The main advantage of PVC sheets is that the entire roof membrane can be joined by welding the joints with solvent or with air heated to 425 °C. This membrane can then be welded to metal flashing that has been factory-coated with PVC. The result is a uniform, watertight roofing assembly. PVC sheets remain elastic at temperatures as low as -40 °C. They are ideal for roof repairs, because of their very high permeance.

Loss of plasticizers was once a major concern, as it caused embrittlement in the PVC sheets. This is now considerably improved by using high molecular weight plasticizers that have less of a tendency to volatilize or migrate out of PVC resin.

Membranes of this type must meet CAN/CGSB 37.54-95. PVC sheets have good resistance to industrial pollutants, bacterial growth and extreme weather conditions. Minor damage to the sheet during installation or in service can be easily repaired by patching the hole using heat or solvent. PVC is incompatible with bituminous materials. Installation by conventional roofers is therefore risky, because care must be taken to avoid using equipment that has been in contact with asphalt. Moreover, some PVC sheets are incompatible with phenol-based insulation, certain wood fibres, and polystyrene insulation.

- Copolymer alloy (CPA) membranes

The abbreviation CPA includes copolymer alloys and modified neoprenes (chloroprenes). In CPA membranes currently available on the market, PVC accounts for a high proportion (less than 50%) of the alloy. CPA sheets are generally white, reinforced and fairly thin. They can be sealed with hot air either at the plant or in the field. CPA membranes are incompatible with cellular glass insulation and with contaminants from asphalt, tar, oils, and other petroleum products.

- Ethylene interpolymer (EIP) and Acrylonitrile butadiene (NBP)

The abbreviation EIP is used to ethylene interpolymer alloys. The abbreviation NBP refers to acrylonitrile-butadiene copolymers which are fusible membranes. PVC accounts for a high proportion (less than 50%) in the membranes currently available on the market. The EIP sheets are generally a sandy, pale brown colour. They are reinforced, come in very thin plies, and can be sealed with heat. Incompatibilities are generally the same as for PVC, but it is best to check with the manufacturer.

- Thermoplastic oligomer (TPO) and heat-weldable synthetic rubber (EP)

TPO membranes are flexible and heat-weldable, but unlike PVC membranes, they do not lose their plasticizers over time. TPO membranes are thus very likely to become the single-ply membrane of choice over the next few years. The abbreviation EP covers both ethylene-propylene copolymers and thermoplastic olefins (TPO). Contrary to EPDM membranes, EP membranes are relatively stiff at low temperatures but they have the advantages of being inexpensive and heat-weldable.

Generally, EP sheets come in light colours and are reinforced. The plies are usually thin and can be sealed with heat. Most often the sheets are white or black, with a blue underside but many other colours are available. There are almost no materials with which EP membranes are incompatible (in case of doubt, check with the manufacturer). EP membrane is used in many environmental applications (for example, to line landfills and the inside of holding tanks for waste oil and animal fats).

- Polyisobutylene (PIB) membranes

PIB, a thermoplastic copolymer of isoprene and isobutylene, contains carbon black and anti-ageing agents. PIB is typically more soluble and more rubber-like than polyethylene or polypropylene. It is also generally more resistant to extreme weather conditions and remains more flexible at lower temperatures. PIB is subject to creep if it is not mixed with other polymers or reinforcement. It is generally manufactured in sheets about 1.5 mm thick, with an unwoven polyester lining about 1 mm thick, which acts both as a reinforcement and as protection against any sharp edges in the deck surface. The joints are sealed with adhesive tape or sealed with solvent. PIB sheets can be used either for ballasted roofs or for roofs adhered with heated asphalt or with cold-applied bitumen coatings.

PIB sheets consist of a single layer of polyisobutylene plastic. They are similar to PVC sheets in their main properties but they are compatible with bitumen. PIB also remains flexible at temperatures as low as -70°C. It is resistant to UV rays and is only available in black.

- Chlorosulphonated Polyethylene (CSPE)

CSPE is better known by the trade name Hypalon. These membranes consist of a single layer of chlorosulphonated polyethylene plastic reinforced with woven polyester. This kind of membrane does not react with acid and alkalis and is most often used in dairy operations and marine environments. Its main properties are similar to those of PVC and Hypalon sheets can be sealed using solvent or a hot iron. Hypalon retains its elasticity at temperatures of -45 °C. It is highly resistant to ultraviolet rays. The standard colours are white, black, and blue, but other colours are available on request.

- Chlorinated Polyethylene (CPE)

The abbreviation CPE refers mainly to the chlorinated polyethylene family. CPE sheets are generally white, reinforced, relatively thin and can be heat-sealed. They are used mainly to line tanks that will hold corrosive materials or animal waste. The joints can be sealed either at the factory or in the field. CPE membranes are generally incompatible with perlite, with certain wood fibres, with cellular glass insulation, with hydrocarbon contaminants and with oxidizing elements (those to the right on the periodic table).

Polyurethane foam (SPF)

Sprayed polyurethane rigid foams (SPF also known as PUF) were first developed in the late thirties and used during the war to strengthen aircraft wings. Commercial use in different industries started only in the late fifties. The sprayed-in-place roofing system was introduced in the early 1960's.

This system is made up of three components: PUF, a protective cover and a vapour barrier. PUF forms a closed cell waterproofing barrier and provides insulation. The foam is made from the combination of two materials, a resin (containing polyol, catalyst, blowing agent, surfactant, etc.) and a polyisocyanate component. Their combination during application from a two-head spray gun produces a polymeric structure and a vapour that forms of bubbles before the foam becomes rigid. During the chemical reaction it expands 20 to 30 times its original volume within seconds. Minimum thickness of the foam layer is 25 mm.

The use of SPF in roofing faced many problems in early years, that were related to the ambient temperature. On hot days the foam reacted too rapidly leaving a rough texture, while on very cold days it did not react leaving the material in a liquid form. Accordingly, attention to environmental conditions (temperature, wind, moisture on deck) is necessary. PUF, once considered only as a reroofing alternative to BUR, is now being used in a wide range of new construction projects.

Since urethane foam is very sensitive to UV radiation, it must be protected in some manner. Various elastomeric coatings and latex paints have been used for this purpose. In some cases, mineral roofing granules are sprinkled into the coating when wet. They improve abrasion resistance, weathering characteristics and fire resistance. Coatings must have high tensile strength, elongation, and water transmission resistance, since water is foam's prime enemy.

A report detailing observations on the performance of sprayed polyurethane foam roofs was recently published. The inspection of roofs was random and the oldest roof was 26 years old. In general, the author of that report indicated no major problems with the system. In 1995, the National Roofing Foundation (a nonprofit corporation separate from National Roofing Contractors Assoc.) designed a field research program to assess the performance of aged SPF systems. The study is carried out jointly between the NRCA and the Structural Research Inc. Some results will be available in the near future.

Metal Roofs

The market share of metal roofs has been increasing over the last few years.

Performance problems

Performance of a roof system can be affected by design features, material selection, installation procedures and maintenance programs. These aspects can be improved by continued technical training of roofing designers and installers, and the marketing of tested materials, along with the dissemination of knowledge of field practices.

The performance of "older" generic single-ply systems such as SBS, APP, EPDM and PVC is well known. But in recent years, a multitude of new plastics has literally invaded the heretofore somewhat conservative roofing industry. Some of these plastics are new molecules created by chemical reaction. Others are simply new mixtures that modify the physical properties of their components, somewhat like metal alloys. These new plastics open endless opportunities to create materials that are tough, strong, rot-resistant, water-repellent, and easy to install with permanent joints.

Effective sealing of joints is critical to the success of single-ply membranes. Failure to do so, for even a few millimetres of joint, can result in a roof leak. There is no second line of defence against water entry, as there is with the multi-ply BUR. Quality control of jointing is easier in the factory than in the field. For this reason, and to speed up field application, suppliers may make large membranes (15 m by 45 m) comprising a number of narrower strips of membrane joined at the factory.

In 1974, practically no one had even heard of EPDM membranes. By 1985, single-ply membranes made of PVC, Hypalon, PIB, EPDM, and other such materials accounted for 40% of the total U.S. roofing market. By 1986, single-ply membranes had taken over 51.7% of the total roofing market. EPDM alone accounted for 54% of all single-ply *membranes, or 28% of the total market for roof membranes. Part of the reason, of course, was that by this time the cost of this material had dropped as low as $CAN 3.50 per square metre ($US 0.25 per square foot). In Canada, a similar shift in the market is expected any time. As in the United States, single-ply membranes will gradually replace conventional bituminous membranes.*

Single-ply membranes generally last longer with no apparent degradation when exposed to ultraviolet radiation. They have a very low expansion coefficient, close to that of wood and concrete, and are often installed on wood or concrete decks. Even when these membranes are installed on flat roofs and exposed to severe water build-up, they do not rot or degrade. Single-ply membranes are often used to seal water tanks and swimming pools. In most cases, neither the membrane, nor the reinforcements, nor the joints are affected by the water in any way.

For any improvement to take place in a component or system it is imperative to know of problem area, the observed deficiency, and its probable cause. Any component that does not fulfill its function can impair the overall system's performance. Any failure needs thorough investigation of the site conditions and laboratory testing of samples for proper assessment.

Some of the failure mechanisms in membranes experienced by the industry are given below. It must, however, be emphasized that these conditions may not be generalized or considered as widely prevalent phenomena. The probability of occurrence is like any other accident that is the culmination of a host of circumstances.

- Pinhole in a cured neoprene sheet when received at the construction site that had gone unnoticed during quality control.
- Swelling of a synthetic rubber sheet due to exposure to oil and plastic roofing cement.
- Punctures caused by foot traffic on a roof.
- Stains showed on a sheet membrane (a case of bituminous fractions diffusing through the sheet and affected by UV radiation). No leakage reported.
- Fish-mouthed lap joint in an EPDM sheet (a case of excessive solvent wash or adhesive swelling the sheets).
- Lap joint pulled apart or easily opened by hand due to many voids in an EPDM sheet.
- Brittle, shrunk and pulled free edge flashing in a PVC membrane (a case of loss of plasticizer).
- Impact fracture owing to a hardened PVC membrane.
- An end lap joint of a modified bituminous membrane, pulled back (a case of negligence: factory wrapping label stuck on the sheet prevented bonding of the mopped joint).
- Lap joints of a modified bituminous (MB) membrane contained air pockets (because the sheet due to its thickness did not flex to allow full embedment in asphalt).
- Degradation of MB due to overheating by torching during application.

- Delamination of MB membranes due to insufficient heat causing blistering.
- Misalignment of rolls causing wrinkles which contain unadhered areas that obstruct water flow and damage the membrane where there is pedestrian traffic.
- Loss of thermoplasticity owing to overheating of rubberized asphalt (RA) during site application.
- Pinholing and blistering due to foaming of hot RA on a wet/moist deck.
- Loss of adhesion due to moisture and surface contaminants on the deck in liquid-applied membranes.
- Cracking of membrane with cracks in concrete deck due to excessive adhesion and low elongation of liquid elastomer.
- Impact damage of polyurethane foam.
- Delamination of foam layers, i.e. between passes.
- Spalling of weathered elastomeric coating on PUF.

Conclusions

It may be appropriate to repeat the often-stated caution for the manufacturer, designer, contractor and workers. They should each have adequate knowledge and training and should employ great care in conducting their part of the job to make the roof perform well.

Thermal analysis shows much promise in providing quick and reliable data regarding the stability of polymeric roofing membranes. It has been shown how the relative stability of PVC and EPDM membranes can be determined by TG, oscillating-DSC, DMA and TMA. Each technique provides information which is complimentary to the other. Furthermore, this data can be of assistance when trying to understand why a membrane is exhibiting peculiar behaviour.

In the future, one would hope that these techniques be incorporated in to the relevant membrane standards. In Canada, the next version of the PVC standard will be addressing this issue. Another aspect to be considered is the use of these techniques in service-life prediction. Using a kinetic approach it may be possible to determine the approximate service-life of some of these materials. Work in this area, has recently been initiated at NRC and data will hopefully be forthcoming in the near future.

This paper dealt with the membranes and the standards requirements for their performance. The total roof involves many other aspects that are equally important and have been dealt with in this seminar.

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