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Characteristics of Membranes and Insulations Used for Low-Slope Roofs

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A. Abstract

This paper presents the types and performance characteristics of membranes and insulation materials used for low-slope roofs.

B. Introduction

The envelope of a building serves the essential function of sheltering occupants from external factors. It must also keep them warm during winter, cool in the summer, dry in all seasons, and safe from wind and tornadoes. A critical component of any building envelope is the roof, which should be comprised of high-performance, durable materials capable of protecting a building from nature's harshest elements, and must also provide water tightness and near-continuous protection from moisture and vapour, ultraviolet (UV) exposure, cyclic thermal loads, cold, noise, wind and fire.

A roof *assembly* is comprised of a roof *system* supported by a roof deck. The roof *system* is made up of the elements that cover, protect and insulate the roof against the external environment. Roof systems vary from the traditional (e.g., shingles for sloped roofs and built-up roofing) to the non-traditional (e.g., polymer-based single-ply or modified bitumen). They also vary according to where the waterproof membrane is located within the system. The conventional method is to have the membrane above the insulation and exposed to the environment. Alternatively, in a protected system, the membrane is installed directly above the deck (or on a levelling board on a steel deck) and is covered with the insulation.

A list of common roofing membranes is given in Table 1. For each membrane 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 offer a number of different products, which may be un-reinforced or reinforced with different fabrics; developed for protected or exposed applications; designed for various seaming and attachment methods; and available in different colours.

For several decades, built-up roofing (BUR) was the predominant option for low-slope roofs. The addition of a new generation of roofing systems has greatly expanded the number of options, and the knowledge designers need to acquire, and also raises questions such as:

- How do the various roofing systems differ?
- How do the newer systems behave?
- Is there a perfect system?

This paper will provide information to help designers answer these questions.

Table 1. List of Common Roof Membranes

Membranes	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
Sprayed Polyurethane Foam	SPF
Ketone Ethylene Ester	KEE

C. Canadian Roofing Market

According to the last survey (2000) conducted by the Canadian Roofing Contractors' Association (CRCA), the average sales volume in Canada in 2000 was $3.7 million; it was projected to increase to $3.9 million for 2001 [1]. In 2000, new construction and re-roofing had equal market shares for both low- and steep-slope roofs. Figure 1 shows the market share (new construction and re-roofing) for the main types of low-slope roofs used in Canada.

For the United States, the average market share (low-slope) for new construction and re-roofing are given in Figure 2. More details can be found in the 2004 National Roofing Contractors Association (NRCA) Survey [2].

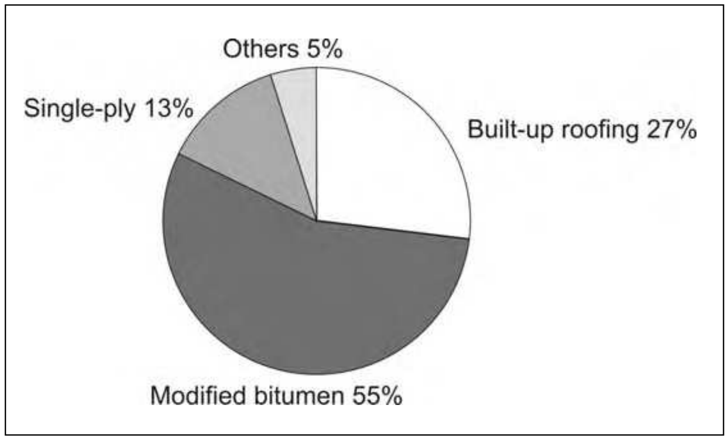

Figure 1. Average market share for low-slope roofs in Canada in 2000 [1]

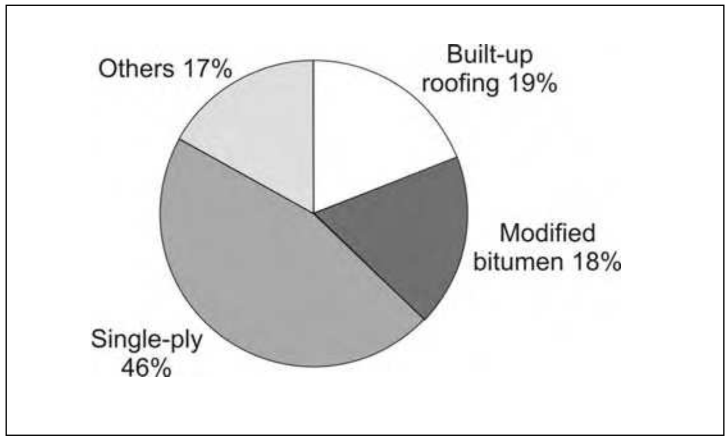

Figure 2. Average market share for low-slope roofs in the U.S. for 2004 [2]

D. Roof Membranes

The terms "sheet" and "membrane" tend to be used interchangeably. However, by definition, a membrane is the finished waterproofing layer comprised of one or more prefabricated sheets. Therefore, a single sheet is the membrane in a single-ply application, but a modified bituminous membrane may have two sheets—a base and a cap. Most membranes are composed of mastic, which is the waterproofing component, and reinforcing fabrics, which give the membranes specific physical and mechanical properties.

Roof membranes are fabricated from strong, flexible waterproof materials. They may be installed in multiple layers (as for a built-up roof) or they may consist of a single-ply membrane. The reinforcing fabrics in membranes are made from felt, fibreglass, or polyester, which are laminated to or impregnated with a flexible polymeric material to provide strength. These polymeric materials range from bituminous hydrocarbon (e.g., asphalt) to synthetic polymers such as ethylene-propylene-diene monomer (EPDM), poly(vinyl chloride) (PVC) and thermoplastic polyolefin (TPO).

Built-up roofs consist of bitumen (Note: for the purposes of this paper, "bitumen" and "asphalt" are used interchangeably) reinforced with roofing felts and aggregates that protect the bitumen from UV radiation and oxidation [3].

Bitumen is a complex mixture of organic and inorganic compounds. The main organic compounds are asphaltenes and maltenes, which are responsible for the viscoelastic properties of bitumen [4]. Despite its natural viscoelastic properties, unmodified bitumen cannot be used in roofing applications because of its inherent limitations, such as brittleness at low temperatures and a tendency to flow at high temperatures. Therefore, attempts have been made to improve the properties of bitumen by combining it with natural or synthetic rubbers or lattices, to obtain new materials that have high elasticity.

Polymer-modified bituminous membranes were developed in Europe in the mid 1960s and have been in use in North America since 1975. Modified bitumens include natural rubber and more complex synthetic systems, such as block copolymers and polymer blends. The most common modifying polymers are styrene-butadiene-styrene (SBS), butyl rubber, ethylene vinylacetate (EVA), atactic polypropylene (APP) and natural rubber. Polymers such as APP or SBS impart flexibility and elasticity, and improve cohesive strength, resistance to flow at high temperatures and toughness [5].

The development of synthetic bitumen materials was prompted by the following factors:

- The energy crisis of the early 1970s resulted in an increase in the cost of petroleum-based products. The unpredictability of the sources of oil supplies meant that the quality of bitumen was not consistent. This, in turn, affected the quality of roofing materials.
- Inflation due to the energy crisis raised the cost of labour-intensive built-up roofing, thus making the alternatives more economically 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 1960s, new structural design principles gave rise to lightweight structures that resulted in a need for lighter roofing systems.
- New roofing materials offered design flexibility by permitting the construction of highly insulated roofs and decks with unusual architectural configurations.
- Better corrosion-resistant metals became available.

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

Polymers are giant molecules of different chemicals. 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) (PVC), polyethylene (PE). Monomers may have the same or different chemical compositions. Similarly, esters are a family of chemicals whose macromolecules are known as polyesters, which are used in synthetic fibres, filaments, threads and fabrics. In the field of polymer chemistry there are many terms related to internal structure, such as monomers (as in EPDM), co-polymers [as in vinylidene chloride (saran wrap)], and block co-polymers (as in SBS).

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 polymer system; for example, EPDM is formed by adding sulphur to the mixture of ethylene propylene-diene monomer. The sulphur forms linkages between the polymer molecules in a process known as vulcanization.

Reinforcements play a very important role in the performance of membranes. Conventional roofing felts are made of organic fibres and are impregnated with asphalt. They act as binders and reinforcement for built-up roofing (BUR) systems. In recent years, non-woven fabrics have become popular.

Most roofing reinforcements are woven fabrics or mats and scrims of non-woven glass fibres and synthetic fibres placed within the body of the membrane. In some cases, a lightweight reinforcing mesh is incorporated to act as a carrier, which facilitates manufacturing and adds to the dimensional stability of the sheet. 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 reinforcing fabrics include tensile strength, high initial elastic modulus, dimensional stability, tear strength, puncture resistance, flexural stiffness, and absorption and fatigue resistance. The tensile strength and elongation properties can be varied to meet the design requirements.

E. Performance of Roof Membranes

Performance Requirements/Criteria

Note: “requirement” and “criterion” are used interchangeably in this paper, i.e., both qualitative and quantitative aspects are implied.

Regardless of the material, there are several performance considerations that must be taken into account when selecting a roof membrane. Durability is the most important consideration. To deliver good performance a roof must:

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

Exposure of the membrane to temperature, solar radiation, water, wind and pollution will induce physical and/or chemical changes that negatively affect the properties of the membrane. This deterioration can be made worse as a result of roof traffic, poor workmanship and lack of maintenance.

One way to predict the performance of a membrane is to identify the physical, mechanical and chemical properties essential for its performance, and to quantify them either on the basis of experience or by testing many products in the same generic class. The values determined for these different properties constitute the performance criteria for a specific class of product tests. These criteria can then be applied, with or without modifications, to other generic types of membranes.

Roofing materials are subjected to a wide range of temperature and load conditions. For example, in northern climates, the temperature of an asphalt or black roof membrane could be as high as 100°C on a hot summer day and low as -40°C in winter. Moreover, the material has to sustain the stresses generated by thermal expansion and contraction. Therefore, good performance at both high and low temperatures is required. Critical properties such as high softening points, tacking and flow resistance at elevated temperatures, impact and crack resistance, cohesive strength and high elastic modulus are required [5].

The durability of polymeric roofing membranes is evaluated using various test methods. The mechanical properties of polymeric materials have two facets: one is the macroscopic behaviour and the other the molecular behaviour [5]. Engineers, architects and roof designers are concerned only with the description of the mechanical behaviour (physical properties) under the design conditions. The evaluation of the mechanical properties of roofing membranes (tensile properties at different temperatures, load at break, elongation at break, and energy required to break) provides information about the material's structural behaviour and how it can be improved, but does not offer an explanation. If the failure is related to molecular activity, additional information is necessary to comprehend the problem fully.

Current laboratory procedures used to evaluate the durability of roofing membranes utilize artificial weathering devices, which attempt to simulate the primary weathering agents, namely solar radiation, temperature, ozone and moisture. After the use of the artificial weathering device, the physical properties are usually compared with an un-aged or "original" sample, with the results stating "Retains x% of the original physical properties after aging" [5]. Some of the requirements and common tests that are relevant to field performance are:

- *Tensile or breaking 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 those from shrinkage due to low temperature or membrane creep. The minimum strength requirement also applies to the weakest direction because 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.
- *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 cohesiveness of the joining matrix. In addition, any voids left in the joint tend to blister and weaken the joint's 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 promote water leakage. Better test methods for assessing lap-joint integrity are required.
- *Crack-bridging ability.* Many shrinkage cracks are present in concrete roof decks. These cracks, which may be up to 3 mm wide, open and close cyclically as a result of structural movement and thermal variation. A roofing membrane adhered to the substrate at these locations must be capable of bridging the gap and handling movement. It is difficult for a well-adhered membrane to provide this capability because the elongation may be very high at the gaps. The crack-bridging test is applicable to both sheet and liquid-applied materials but is especially crucial for liquid-applied materials.
- *Tear resistance.* The likelihood of tearing is greatest where an "oblique" stress occurs along the edges of the membrane, producing a torsional effect. This stress can result from an oblique pull at the rollers during the manufacturing process; it can also result at the points of stress concentration along the edges due to structural movement and pulls on the sheet during application. Good tear resistance is important especially where mechanical fasteners are used and where the membrane must withstand traffic.
- *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 important factors affecting durability. The heat-aging test simulates the accelerated effect of solar heat. The results are compared with the properties of unexposed material to predict durability.
- *Granule embedment.* The exposure of bituminous surfaces to weather elements causes degradation of the bitumen that leads to the loss of adhesion of the protective granules or gravel. Good granule embedment is vital to the durability of 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, the dead-load contributed by people and machinery during construction or service, or a single human foot on a heated membrane during installation. A high degree of static puncture resistance is needed for plaza decks.
- *Dynamic puncture resistance.* This test simulates impact from falling objects (e.g., a workman's tool, hail, foot traffic) to assess the ability of a membrane to remain waterproof. The membrane is tested using a falling load fitted with an indentor tip.
- *Dimensional stability.* This important property is a measure of the dimensional change due to exposure to elevated temperatures, relaxation, loss of volatile components and incompatibility of materials. Excessive shrinkage due to dimensional instability may cause a membrane to pull away from the flashing. Dimensional instability may also cause expansion, resulting in wrinkles and subsequent failure due to cracking.
- *Permeability.* This property is related to water vapour transmission or permeation. Good permeability allows moisture trapped beneath a membrane to dissipate through the membrane without adversely

affecting its watertightness. The rate of water vapour transmission is related to the properties of the vapour barrier in the system, and affects the roof assembly design.

Results from these tests greatly increase the ability of roof designers to make appropriate membrane selections that will maximize roof durability and longevity.

Thermal Analysis

As mentioned, there is a wide range of roofing materials, from asphalt-based or modified-asphalt (APP and SBS) to polymer-based materials such as TPO, PVC and EPDM. This broad range of products provided the motivation for the international roofing industry to use both engineering and chemical principles for roof design. In 1988, an international roofing committee (CIB/RILEM) was established to investigate the application of thermal analysis in the characterization of roofing membranes [5]. These techniques, in conjunction with traditional engineering techniques, provide insight into the performance of roofing membranes [5-8].

Until recently, thermal analysis was not widely used in the roofing industry. However, 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). These techniques can play a role in the decision-making process for roofing material selection. For example, T_g is an important property that should be considered for the cold-temperature performance of roofing membranes. At a temperature below the T_g the material will be rigid and hard; yet, above the T_g the material will be flexible. Generally, the strength of polymeric materials above the T_g is lower than the strength below this temperature. Other properties that vary with T_g are the coefficient of thermal expansion (CTE) and the heat capacity [3, 9-12].

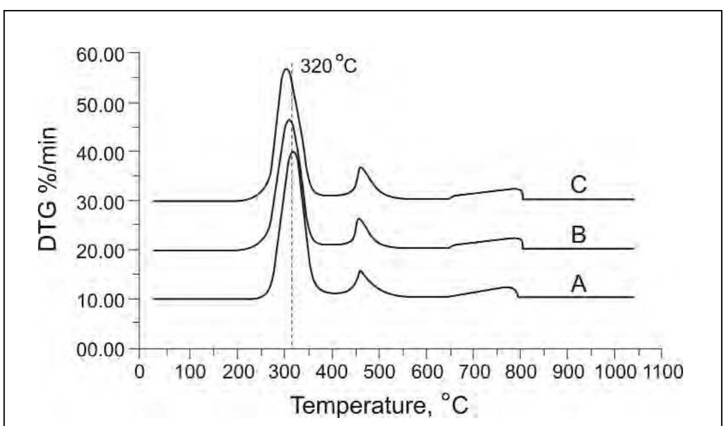

Figure 3. Derivative of weight loss (DTG) curves of an in-service PVC roof obtained by thermogravimetry:
A) Sample #1, bottom sheet
B) Sample #1, top sheet, area 1
C) Sample #2, top sheet, area 2

There are four main thermoanalytical techniques used to determine and monitor changes in a roofing membrane. They are:

1. thermogravimetry (TG)
2. differential scanning calorimetry (DSC)
3. dynamic mechanical analysis (DMA)
4. thermomechanical analysis (TMA).

At this point in time, the most popular techniques used for roofing are TG and DMA.

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

  Figure 3 shows the derivative of the weight loss (TG); i.e., DTG (the amount of material decomposed per unit time or temperature) curves obtained from the thermogravimetric analysis of two specimens (Samples #1 and #2) taken from the same in-service roof.

  - Curve **A** is the DTG for the bottom sheet (underlap) of Sample #1 (seam cut) used as a control because it has been shielded from environmental conditions.
  - Curve **B** is the DTG for area **1** of the top sheet of Sample #1.
  - Curve **C** is the DTG curve for area **2** on Sample #2.

  As can be observed, the maximum of the DTG for curve **A** (control) occurs at 320°C whereas the maximum of the **B** and **C** curves occurs at a lower temperature. The figure demonstrates the thermal stability of the samples and how this stability varies within the same roof, with Curve **A** indicating that Sample #1 is the most stable.

- *Dynamic Mechanical Analysis (DMA)* [13-17]: The DMA technique measures the stress-strain relationship for a viscoelastic material. The storage modulus (E') is a measure of recoverable strain energy in a deformed body. The loss modulus (E'') indicates the dissipation of energy as heat due to the deformation of the material. The ratio E''/E' yields the loss tangent or damping factor (tanδ), 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 E', E" or tanδ plotted as a function of time or temperature. In general, the most intense peak observed for either E" or tanδ, in conjunction with a relatively pronounced drop in E', corresponds to the T_g. However, to prove that this relaxation event does correspond to a T_g, a dynamic mechanical analysis multiplexing experiment would be required to establish the activation energy. The T_g may be affected by the cross-link density, or degree of crystallinity, and is directly related to the amorphous region within a polymer.

Figure 4 shows the loss modulus (E") curves for two specimens from a TPO sample. One specimen was unheated and the other heated at 116°C for 14 days. The maximum of the curves corresponds to the T_g of the samples. The T_g of the unheated sample occurs at 3°C lower than the T_g of the heated sample. The figure illustrates the usefulness of the DMA technique. Care should be taken when reporting the T_g obtained by DMA because the T_g determined by this technique (or through other dynamic techniques) is not only heating-rate dependent but also frequency dependent. In addition to heating rate and frequency, the mechanical/rheological property (E', E" or tanδ) used to determine the T_g must also 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 [5].

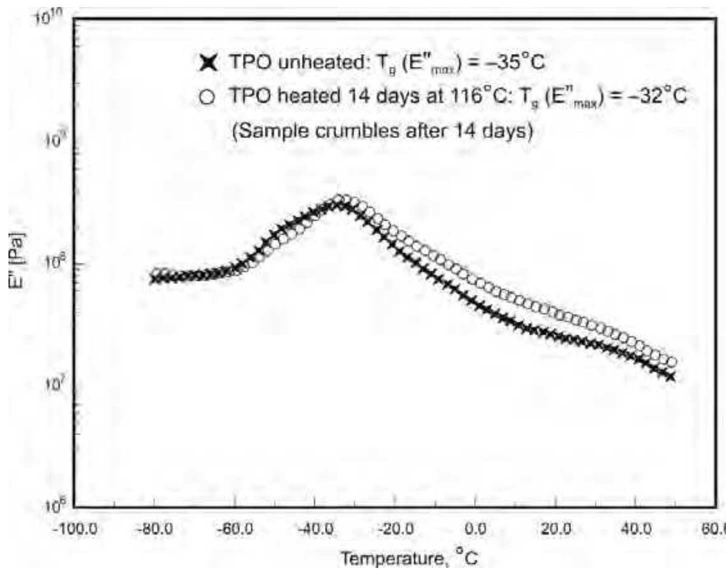

Figure 4. Loss modulus (E") curves for two thermoplastic polyolefin (TPO) specimens obtained by dynamic mechanical analysis

F. Membrane Characteristics

1. Bituminous built-up roofing (BUR)

Bituminous materials used in built-up roofing include (a) asphalt obtained in petroleum processing and (b) a product extracted from coal known as coal-tar pitch (also referred to as tar or pitch). In Canada, coal-tar pitch is generally not available unless it is imported. Asphalt used for saturating organic felts is commonly called No. 15 because the earlier types weighed 15 lb./100 ft.². Coal-tar pitch and asphalt-impregnated glass fibre felts are used as built-up roofing plies. Heated asphalt is then mopped on each felt layer to bind the layers together into the finished multi-ply membrane.

Many built-up roofing problems, such as blistering, are related to moisture and air voids in the membrane. Organic felts can lose strength due to moisture absorption resulting from improper storage or lack of protection from rain during installation. Sometimes moisture is trapped where the mopping of asphalt under the felt has been skipped. Also, synthetic fibres from rags sometimes get included in the felts during the manufacturing process, resulting in poor asphalt saturation.

Glass fibre felts are quite porous and provide good adhesion. Their use in flashing is not recommended because flexibility is critical. During installation, foot traffic over newly placed felt and asphalt causes the asphalt to "squeeze out," which could result in a void and a lack of adhesion in the membrane—a potential source of moisture problems.

A very common source of problems is heating the asphalt such that the manufacturer's recommended viscosity range is exceeded. This makes mopping easy, but hardens the asphalt and reduces both its softening point and coefficient of linear thermal expansion, which causes shrinkage cracks and alligatoring.

Other built-up roofing problems include:

- shrinkage of the membrane, which pulls flashings away, and is caused by a lack of adhesion of the roofing system to the deck, and
- membrane slippage, which can occur if the softening point of the asphalt is too low with respect to the roof slope, or if the amount of inter-ply asphalt is excessive.

2. 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 manufacturing process is basically the mixing of components, the amount of modifier can be varied according to the characteristics required for the membrane. The two most widely used bitumen modifiers are styrene-butadiene-styrene (SBS) and atactic polypropylene (APP). 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. There are about a dozen different SBS grades that accentuate one or more properties beneficial to the manufacturing and performance of membranes. APP is a by-product of the manufacture of isotactic-polypropylene (IPP). It comprises 25–35% of the modified compound, with its primary function being to improve the mechanical properties of the finished membrane. APP-modified membranes have higher strength and lower elongation compared to SBS-modified types. A small quantity of filler provides rigidity to the compound but large quantities reduce flexibility and adhesion. Consequently, the best products have the least amount of filler.

Proper modification of bitumen results in a product whose performance characteristics are superior to those of unmodified bitumen. Various types of membrane reinforcements, particularly glass and polyester composites, further improve its properties. Granules protect the surface from the degrading effect of UV radiation. 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 for its intended use. The membrane sheets can be up to about 5 mm thick.

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. Since open-flame torching is considered a fire hazard, some manufacturers have introduced an electric heat-welding process. Overheating modified bitumen degrades the mastic and leads to poor adhesion and weak lap joints.

3. 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. They are applied hot to form an impermeable monolithic membrane over the surface that is to be waterproofed. The surface may be of 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, which is known as a fully reinforced or two-ply system.

Both membrane types use bitumen 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 UV radiation.

4. Polymeric sheets

Single-ply polymer roofing membranes have been available in North America since the 1950s. Many new products, such as polychloroprene (CR), chloro-sulphonated polyethylene (CSPE), EPDM and PVC, were introduced to the market at that time. These products required novel installation techniques, and initially many failures occurred.

Today, there are many companies involved in the manufacturing of single-ply membranes. The advantages of such systems include the speed of installation and the elimination of open flames or heated asphalt. However, these systems 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 radiation, heat and bacterial attack.

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 main categories of polymeric sheets: elastomeric and thermoplastic.

4.1. 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 and nitrile. They are compounded with polymers and ingredients such as fillers, anti-degradants, processing oils and aids, to impart the required properties. Polymers provide the muscle and fillers the bones. Stabilizers (e.g., anti-degradants) improve the weathering properties of the membranes. The most commonly used elastomer in roofing is EPDM. This compound contains 30–50% polymer (ethylene-propylene-diene monomer), 20–30% carbon black and 30–50% extender oil, sulphur, 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 cross-linked network. This is generally an irreversible process. The most common method of vulcanization involves 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, and other enhanced physical properties.

The non-vulcanized, or uncured, rubber sheets 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 strength and other mechanical properties, as well as excellent resistance to UV radiation, ozone, and many oils and solvents.

Field seaming of some vulcanized sheets is known to cause problems but is continuously being improved. Maximizing the amount of seaming done in the factory reduces the amount of field seaming and hence the likelihood of problems. Some aspects have been discussed in the section on lap-joint integrity. The proper choice of adhesives, care in the preparation of the seam area, skillful application, and adequate curing time can produce a durable joint. It should be noted that the National Institute of Standards and Technology (NIST) has studied the use of tapes instead of liquid adhesives for seaming.

4.2. Thermoplastic sheets

Thermoplastic polymers soften when heated and thus can be easily extruded or moulded. They are distinguished from thermosets by the fact that there is no cross-linkage or vulcanization of the molecules. Welding them together using heat or a solvent is easy and creates new molecular linkages that last throughout the service life of a membrane.

- *PVC*

  Poly(vinyl chloride) is one of the most versatile thermoplastics available today. Its use in roof covering began in the 1960s. The compounded plastic is the key element of a PVC sheet, which determines the final characteristics 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 cost of raw materials 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 UV radiation during service. Pigments are added to colour the plastic material.

  The loss of plasticizers became a major concern in the late 1980s and early 1990s because this loss causes the PVC sheets to become brittle. However, there has been considerable improvement through the use of high molecular weight plasticizers that have less tendency to migrate out of the PVC resin. Most of the PVC sheets available today are reinforced with glass and/or polyester fibres or fabrics, which provide dimensional stability and improve tensile strength.

  PVC sheets have good resistance to industrial pollutants, bacterial growth and extreme weather conditions. Moreover, minor damage to the sheet during installation or in service can be easily repaired by patching the hole using heat or solvent.

- *Thermoplastic (TPO) or flexible polyolefins (FPO)* [18]

  "Thermoplastic" is a generic term in polymer science. It encompasses a class of polymers that soften when heated, in a reversible process. The term olefin is a generic name for any molecule containing carbon-carbon double bonds. The modern name for this family of molecules is alkenes. Thermoplastic roof membranes have been in service in Europe for about 15 years and their use in North America is increasing. As expected with any new product, there has been a learning curve associated with the installation and maintenance of TPOs.

  The polymer used in TPOs is not specified in ASTM standard D6878-03 but the standard does dictate that "the sheet shall contain ethylene and higher alpha-olefin polymers, copolymers, and mixtures thereof, in amounts greater than 50% by weight of the total polymer content." Using this definition in combination with the definition of olefin, there is an endless list of chemicals that could meet this requirement (e.g., polyethylene, polypropylene, isobutylene, and their derivatives) [19-23].

5. Cold-applied liquid compounds

This category of membrane materials consists of emulsions and solutions of (a) various resins or elastomers, such as polyurethanes, silicones and acrylics and (b) bitumens and modified bitumens. To protect membranes from solar radiation, their surface coatings may contain white pigment or aluminum flakes, or they may consist of a vinyl film. These liquids are generally applied by spraying or with rollers. The emulsions cure slowly at low temperatures and they cannot be applied at a temperature below that at which water freezes because the solution forms a film too quickly. Cutbacks (solutions) and emulsions (water dispersions) of asphalt and coal-tar pitch are also used in various types of cold applications of built-up roofing, and polyester mats are used as alternatives to conventional felts for plies. The market share of cold-applied built-up roofing is small, and because of higher costs and lesser availability, asphalt is used more often in this type of application.

Appendix 1 provides a brief description of other roof covering materials, such as polyurethane foam and metal.

G. Insulation Materials for Roofing

There are many types of and arrangements for insulation materials used in roofing systems [24]. According to the last survey conducted by the Canadian Roofing Contractors' Association [1], the low-slope roof insulation market shares were as follows: polyisocyanurate 55%, expanded polystyrene (EPS) 17%, wood fibreboard 15% and others 13%. For steep-roofs they were: polyisocyanurate 38%, EPS 15% and extruded polystyrene (XPS) 8%, for a total of 61% (Figure 5).

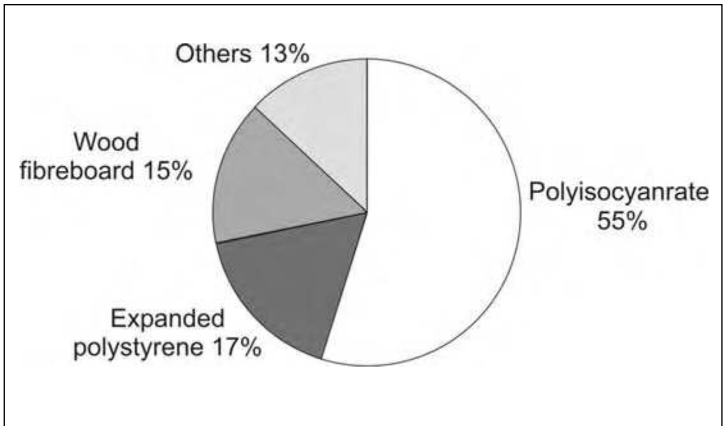

Figure 5. Average market shares of insulation for low-slope roofs in Canada in 2000 [1]

The primary function of thermal insulation is to inhibit heat transfer across the roof assembly. Hence, a material that has very high thermal resistance can be used as a thermal insulator. The heat transfer phenomenon across a material or system can occur in three different modes: conduction, convection and radiation. An ideal thermal insulation material has a very low thermal conductivity, a high capacity to absorb radiation, and small cells to inhibit convection without increasing solid conduction. The construction or composition of all thermal insulation is based on the aforementioned three principles to reduce the heat flow across the roofing system.

H. Characteristics of Insulation Materials

Thermal and moisture properties

The most important characteristic of an insulating material is its thermal resistance, or R-value. The thermal resistance of an insulating material can be defined as the temperature difference across it required to produce one unit of heat flow per unit of area [25]. A higher R-value indicates a material with a higher potential as an effective insulator. In the construction industry, the insulating capacity of a material is generally expressed as the R-value per inch of thickness. Most materials sold as building insulation provide an R-value of between 2 and 6 units per inch of thickness.

Table 2 shows the typical properties of several major types of insulation materials used in low-slope roofing applications [26,27]. (Note that the properties shown in Table 2 are representative in nature and should not be considered as exact values.) In addition to the thermal properties, it is also important that insulation materials have appropriate physical and moisture-response characteristics for the long-term serviceability and integrity of the roofing system.

Table 2. Properties of Roofing Insulation#

Material	Density ($kg{\bullet}m^{-3}$)	Thermal Conductivity ($W{\bullet}m^{-1}K^{-1}$)	R-value per inch	Air-Vapour Permeance	Dimensional Stability (%) at 70°C and 97% RH (maximum)	Compressive Strength (kPa) (minimum)	Flexural Strength (kPa) (minimum)
Wood Fibreboard	250	0.051	2.8	Low	N/A**	100	30 to 200 (N)+
Expanded Polystyrene (EPS)	14.8	0.038	3.8	Low	1.5	70 to 210	170 to 350
Paper-Faced Polyisocyanurate*	63.0	0.028	5.2	Low	± 2.0	110 to 140	170 to 275
Foil-Faced Polyisocyanurate*	33.6	0.025	5.8	Impermeable	± 2.0	110 to 140	170 to 275

#Thermal and moisture properties were measured in the National Research Council's Thermal and Moisture Performance Laboratory. Strength- and stability-related indicators were extracted from CAN/ULC Standards S701, 704 and 706.

**R-value per inch depends on the age and thickness of the insulation.*

***N/A – Not applicable*

+Transverse load (N – Newton) at rupture (see CAN/ULC Standard S-706)

R-value plays a very important role in determining the energy (i.e., thermal) performance of roofing systems. However, the overall performance and durability of a roofing assembly depends not only on the thermal response but also on the moisture response of the roofing system [28]. The thermal response of insulation materials in the presence of moisture, and the moisture response of materials under different thermal conditions are interrelated. Together, they play a very important role in determining the energy, moisture and long-term durability of the roof assembly. Improper selection of the insulation material, or its incorrect location within the roofing system, results in lower thermal performance and undesirable moisture condensation inside the roof assembly, which in turn can seriously impair the performance (in spite of how it was designed) and the service life of the roof. In order to avoid such consequences, the insulation tests and properties discussed below, which are commonly referred as the hygrothermal properties, should be applied.

Hygrothermal properties

1. *Air Permeability* (unit: $kg\bullet m^{-1}\bullet Pa^{-1}\bullet s^{-1}$)

   This test measures the airflow rate at a steady state and the pressure differential across the specimen. From these data the air permeability, k_a is calculated as per ASTM Standard C 522, *Standard Test Method for Airflow Resistance of Acoustical Materials.*

2. *Dry Density* (unit: $kg\bullet m^{-3}$)

   The density of a building material is defined as the mass of one cubic metre of the dry material. For practical reasons, the phrase "dry material" does not necessarily mean absolutely dry. For each class of generic material, such as mineral, wood or plastic, it may be necessary to adopt prescribed standard conditions. The "dry weight" can be determined using ASTM Standard C 1498, *Standard Test Method for Hygroscopic Sorption Isotherms of Building Materials.*

3. *Heat Capacity* (unit: $J\bullet kg^{-1}\bullet K^{-1}$)

   The specific heat capacity of a material is defined as the heat (energy) required to increase the temperature of a unit of mass of the material by 1 K [Note: x °C= (273.15+x) K]. ASTM Standard C351-92b, *Standard Test Method for Mean Specific Heat of Thermal Insulation*, can be used to determine the heat capacity of the insulation materials.

4. *Sorption/Desorption Characteristics* (unit: $kg\bullet kg^{-1}$)

   Sorption/desorption characteristics are defined by determining the equilibrium moisture content in the material at different relative humidity (RH) levels. For sorption measurements, the dried specimen is placed consecutively in a series of test environments at constant temperature, with relative humidity increasing in stages until equilibrium is reached in each environment. The starting point for the desorption measurements is from an equilibrium condition very near 100% RH; then the specimen is placed consecutively in a series of test environments, with relative humidity decreasing in stages until equilibrium is reached in each environment. ASTM Standard C 1498, *Standard Test Method for Hygroscopic Sorption Isotherms of Building Materials*, can be used to determine sorption/desorption characteristics of insulation materials.

5. *Thermal Conductivity* (unit: $W\bullet m^{-1}\bullet K^{-1}$)

   The thermal conductivity of a material is defined as the ratio between the density of the heat-flow rate and the magnitude of the thermal gradient in the direction of the flow. Thermal conductivity of building materials increases linearly with the temperature. The most commonly used equipment to measure this property is the guarded hot plate apparatus or the heat flow meter apparatus. ASTM Standards C 177, *Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus*, and C518, *Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*, are widely used for this purpose. Note that R-value = [Thickness (m)]/[0.1761xThermal Conductivity ($W\bullet m^{-1}\bullet K^{-1}$)].

6. *Water Absorption Coefficient* (unit: $kg\bullet m^{-2}\bullet s^{-1/2}$)

   A material that allows liquid moisture diffusion through its boundary surface would undergo a change in weight with time when it is brought in contact with liquid water. The specimen weight increases linearly with the square root of the time before it comes close to the saturation limit. The slope of the line divided by the area of the surface in contact with water is the water absorption coefficient. The water absorption coefficient of a material governs the liquid moisture movement into it. The new CEN Standard 89 N 370 E, *Building Materials–Determination of Water Absorption Coefficient*, can be used to determine the water absorption coefficient of common building materials.

7. *Water Vapour Permeability* (unit: $kg\bullet m^{-1}\bullet Pa^{-1}\bullet s^{-1}$)

   The water vapour permeability is defined as the ratio between the density of the vapour flow rate and the magnitude of the vapour pressure gradient in the direction of the flow. The magnitude of water vapour permeability depends on temperature as well as relative humidity. ASTM Standard E 96, *Standard Test Methods for Water Vapour Transmission of Materials*, can be used to determine the water vapour permeability characteristics of insulation materials.

Mechanical and Physical Properties

In addition to good hygrothermal performance, insulation materials should also have enough mechanical strength and physical stability to satisfy the structural requirements for a particular roofing system. Some basic properties required for this purpose are given in Table 2 and should be determined as explained below.

1. *Compressive Properties of Thermal Insulations* (unit: kPa)

   Properties such as compressive strength and modulus of elasticity describe the response of thermal insulation under compressive loads. ASTM standards C165-05, *Standard Test for Measuring Compressive Properties of Thermal Insulations*, and C1621-04a, *Standard Test Method for Compressive Properties of Rigid Cellular Plastics*, can be used for this purpose.
2. *Dimensional Stability* (unit: % linear change or % volume change)

   Dimensional stability measures the changes in the linear dimensions of a material when subjected to specified thermal and/or humid exposure over a period of time. ASTM Standard D2126-04, *Standard Test Method for Response of Rigid Cellular Plastics to Thermal and Humid Aging*, or a similar standard approved by the industry can be used to assess dimensional stability.
3. *Flexural Strength* (unit: kPa)

   Flexural strength is the resistance to flexural loading of a material loaded under 3-point or 4-point bending. ASTM C203-05, *Standard Test Methods for Breaking Load and Flexural Properties of Block-Type Thermal Insulation*, is used to determine the flexural strength of block-type insulation materials.

I. Conclusions

The main purpose of this paper is to provide comprehensive information about the terminology, characteristics and properties of the numerous types of materials used for low-slope roofing.

Thermal analysis shows much promise for providing quick and reliable data on the stability of polymeric roofing membranes. It has been shown how the relative stability of poly(vinyl chloride) (PVC) and thermoplastic polyolefin (TPO) membranes can be determined by thermogravimetry (TG) and dynamic mechanical analysis (DMA). Each of these techniques provides information that is complimentary to that provided by other thermoanalytical techniques and mechanical tests. Furthermore, these techniques can be of assistance when trying to understand why a membrane is exhibiting peculiar behaviour.

In the future, it is likely these techniques will be incorporated into relevant membrane standards. In fact, this has already started in the U.S. (ASTM International). There may also be increasing use of these techniques for 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-IRC and data are expected in the near future.

The properties of insulation materials play an important role in the performance and durability of roofing systems. This paper briefly defined the basic thermal, moisture and physical properties of insulation materials for low-slope roof construction and also indicated the available standard test methods to determine these properties in the laboratory. These properties need to be well defined and their effect on the overall thermal and moisture management capability of the roofing system be properly understood. NRC-IRC has been conducting research on insulation materials for over sixty years and is currently engaged in developing a better understanding of the application of high-performance thermal insulation in building envelopes. It is expected that with further research, better performing thermal insulation will be incorporated into modern roofing systems.

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Appendix 1

Polyurethane foam

Polyurethane rigid foams (PUF) were first developed in the late 1930s and were used during the war to strengthen aircraft wings. Their commercial use in different industries did not begin until the late 1950s. The sprayed-in-place PUF roofing system was introduced in the early 1960s.

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, a catalyst, a blowing agent and a surfactant) and a polyisocyanate component. Their combination during application from a two-head spray gun produces a polymeric structure and a vapour that forms bubbles before the foam becomes rigid. During the chemical reaction the foam expands to 20–30 times its original volume within seconds. The minimum thickness of the foam layer is 25 mm.

In the early years there were many problems related to ambient temperature in using PUF in roofing. 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 liquid form. Thus attention to environmental conditions (temperature, wind, moisture on deck) is necessary. PUF, once considered only as a re-roofing alternative to built-up roofing, 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 onto 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.

Metal [29]

Metal dates back to Biblical times and has always been coveted as a roofing option. However, the use of metal roofing has been limited historically by its higher initial costs relative to many other material options. The cost of metal roofing improves if the long-term cost of owning a roof is taken into consideration.

In the U.S., metal roofing had a 1% market share (2004). In Canada (2000), it also had a market share of 1%. Metal roofing continues to increase its share of the roofing market as more and more owners and designers seek to minimize life-cycle costs.

As with any material, there are inevitable failures due to its misuse. The use of metal roofing systems requires some knowledge and understanding of the basic elements of the system design. Proper material selection and installation certainly improves the odds for a successful roofing project.

One of the first issues to be decided on is the type of metal to use. There are a variety of choices, including copper, terne, aluminum, stainless steel, carbon steel, zinc, lead, and even titanium. All of them have pros and cons.

Titanium-zinc – This soft gray metal is very popular in Germany and other European countries, and its popularity is increasing in the U.S. The crafted metal is available pre-weathered and in different surface finishes in 0.7 and 0.8 mm thicknesses.

Tin-lead (Terne) – Tin-lead roofs date back to early 20th Century, and many terne roofs can still be seen in the Eastern part of the U.S. Alloy-coated steel is responsible for the popular misnomer "tin roof." Terne actually falls under the carbon steel classification of ASTM A240 while terne-coated stainless is under ASTM 625. Terne has a greater life expectancy than many other roof metal options, at a moderate cost, but it requires a high level of maintenance (painting). Terne-coated stainless is maintenance-free and can be soldered, but is as expensive as zinc, lead, titanium and lead-coated copper.

Lead – This is one of the longest-lasting metals and has been used for more than a millennium in some of the most elegant castles and cathedrals in Europe. It probably outlasts any other type of roof, metallic or not. However, the design must take into account its very high thermal expansion coefficient and its significant weight.

Due to environmental concerns, terne, copper and stainless (which used to have a lead alloy coating) are now using other alloys like tin-zinc.

Copper – This metal is specified in ASTM B370 and lead-coated copper in ASTM B101. Metal is designed by the ounce-weight.

Aluminum – High tensile aluminum offers some structural capability and is more affordable than other metals but causes a great deal of thermal movement due to its extremely high coefficient of thermal expansion. Therefore, detailing must provide for thermal movements and fabrication methods must take its brittle behaviour into consideration. In spite of this, it is a cost-effective option especially for salt-sprayed coastal and acid-rain environments. Aluminum is easily painted and its installation practices are generally consistent with those of coated steel products. Its use is specified in ASTM B209.

Steel – This metal has the lowest cost of all roofing metals as well as excellent structural characteristics. Since this material rusts, a protective coating is required. Coated carbon is still the most popular choice for metal roofing in North America, primarily for economic reasons. For the commercial roofing market, the most common gauge for steel is 24, but it is also manufactured in a 26 gauge. Due to stringent wind test standards (ASTM E1592 and FM4471) developed following hurricanes such as Andrew and Iniki, a 22-gauge material is now being used. One of the drawbacks of this material is that it undergoes 'oil canning.' This is a rippling effect in the panel surface due to stress. Contractors and designers believe that increasing the thickness of the panel will eliminate the rippling effect but it is likely this will add to the cost without solving the problem. More effective approaches that may resolve or prevent oil canning are given in reference 24.

Steel used in exterior applications must be protected from corrosion by coating it. These coatings are applied by continuous hot-dip method and are metallurgically bonded to the base steel. There are three different types of steel coating used in the U.S.: zinc, aluminum and an alloy of the two (i.e., *Galvalume*™). Discussion of the different types of steel coatings is beyond the scope of this paper. Contrary to industry claims, coated steel cannot be welded without damaging the corrosion protection. The weld must be protected from corrosion by using a brush-applied, air-dried paint (e.g., zinc or aluminum particulate).