ROOFING MATERIALS

Roofs are a basic element of shelter from inclement weather. Natural or hewn caves, including those of snow or ice, are early evidence of human endeavors for protection from the cold, wind, rain, and sun. Nomadic people, before the benefits of agriculture had been discovered and housing schemes developed, depended on the availability of natural materials to construct shelters. Portable shelters, eg, tents, probably appeared early in history. Later, more permanent structures were developed from stone and brick. Salient features depended strongly on the availability of natural materials. The Babylonians used mud to form bricks and tiles that could be bonded with mortars or natural bitumen. Ancient buildings in Egypt were characterized by massive walls of stone and closely spaced columns that carried stone lintels to support a flat roof, often made of stone slabs.

As larger and larger structures were desired, building design became an important element in construction. Roofs evolved from a simple covering to roofing systems designed to perform a number of functions to separate indoor and outdoor environments. Selection of roof design depended not only on factors of economy and comfort, but also on the availability of materials and structural and aesthetic factors. Thus, a modern design normally includes a structure to carry loads, insulation to control heat flow, a barrier to control air and vapor flow, and a roofing element to prevent water penetration.

For low slope commercial roofing, bituminous-based roof coverings are the most common systems in the United States. Asphalt-based materials predominate over coal-tar based materials in these systems. For residential roofing materials, various types of roofing products, including asphalt, wood, and tile, are used for both new construction and reroofing.

1. Continuous or Jointed Systems

1.1. Built-Up Roofing

Built-up roofing (BUR) is a continuous-membrane covering manufactured on-site from alternate layers of bitumen, bitumen-saturated or coated felts, or asphalt-impregnated glass mats and surfacings. These membranes are generally applied with hot bitumens or cold applied bituminous adhesives (qv).

The deck may be nailable, eg, wood or light weight concrete, or not, eg, steel or structural concrete. The felts or mats may be organic (cellulose), or fiber glass. The roof slope ranges from dead level (0–2.1 cm/m), to flat (2.1–12.5 cm/m), to steep (12.5–25 cm/m).

1.1.1. Specifications and Application Rates

Specifications as published in catalogs of roofing manufacturers or contractors' associations appear complicated because of the many variations possible. Application methods depend on the type and slope of the deck, the types of insulation and roofing membrane, and the fastening method (Table 1). Built-up roofs generally are not applied to slopes steeper than 25 cm/m because application of hot asphalt (qv) to such roofs is difficult, whereas other forms of roofing, such as shingles, are easily applied.

Table 1. Simplified Hot Applied Membrane Material Specifications

Type	ASTM Specification	Reference
organic ply felt	D226, Types I and II	1
base sheet	D2626	2
fiber glass mats	D2178, Types III–VI	3
base sheet	D4601, Types I and II	4
venting base sheet	D4897, Types I and II	5
surfacings		
organic cap sheet	D371	
fiber glass sheet	D3909	6
asphalt	D312, Types I–IV	7
gravel or slag	D1863	8
asphalt-based aluminum coating[a]	D2824, Types I or III	9
emulsified asphalts[a]	D1227, Types II–IV	10
fibered roof coating[a]	D4479	11

[a] Asbestos-free.

Table 2. Typical Application Rates for BUR Membranes

Material	ASTM specification	Cold applied, L/m[2a]	Hot applied, kg/m[2b]	Reference
primer	D41	0.3		12
bitumen ply	D312, D450		1.22	(7, 13)
adhesive	D312, D450, D3019	0.4–0.8		(7, 13, 14)
bitumen surfacing	D312, D450, D1227	0.8–1.6	2.9	(7, 10, 13)
gravel covering	D1863		19.5	8
slag covering	D1863		14.6	8
asphalt–liquid surfacing/cements		0.6–1.22		(7, 9–11)

[a] To convert L/m^2 to gal/100 ft^2, multiply by 2.45.
[b] To convert kg/m^2 to lb/100 ft^2, multiply by 20.5.

Common BUR systems are installed in different ways: membrane adhered/attached to deck without insulation; insulation adhered/attached to deck with membrane applied to insulation; base sheet adhered/attached to deck, insulation to base sheet, and top membrane to insulation; and membrane adhered/attached to deck and insulation applied over the membrane, the so-called protected-membrane roof.

The components must be anchored as protection against wind uplift, slippage, and membrane movement. Application rates for BUR membranes are given in Table 2. Membrane strength is related to felt or glass-mat strengths and the number of plies. Continuous bonding is inadvisable if the elastic limit of the membrane will be exceeded, which results in the development of splits in the membrane and leads to roof leaks. Nailing or spot adhesion of the first layer provides relief from concentrated strains.

1.1.2. Properties of Ply Felts and Asphalt-Saturated and Coated Felts

The properties of asphalt-saturated and coated felts and impregnated fiber glass mats are given in Table 3. In addition, ASTM D4897 (5) describes an asphalt impregnated and coated glass fiber base sheet that has mineral surfacing on the top and coarse mineral granules on the bottom for use as the first ply of a roofing membrane. The base sheet provides for the lateral release of pressure that might be caused by entrapped vapor.

Table 4 describes properties of ASTM ply felts used for BUR. For additional details, the appropriate ASTM specifications should be consulted (1, 3). Periodic revisions are made by ASTM committees to keep up with current practices.

Table 3. ASTM Requirements for Asphalt-Saturated and Coated Felts for BUR

		ASTM D4601[a]		ASTM D4897[b]	
Property	Organic base sheet[c,d]	Type I	Type II	Type I	Type II
mass, min, kg/m^2[e]	1.8	0.65	0.75	2.44	2.68
mass desaturated mat, min, g/m^2[e]	253	68	83	73	83
mass % mineral matter, max, % passing a 212-μm (No. 70) sieve	60	70	70	60	60
breaking strength, kN/m[f]					
with fiber grain	6.1	3.9	7.7	3.9	7.7
across fiber grain	3.5	3.9	7.7	3.9	7.7
permeance, max, ng/(Pa·s·m^2)[g]	17				
pliability radius, 13 mm, 10 pass, at 23.1°C		pass	pass		

[a] Perforations provide vents for gases liberated during applications[d] (4, 10).
[b] Asphalt-coated glass fiber venting base sheet with fine mineral surfacing on the top side and coarse granules on the bottom side; perforated/embossed or not. The coarse granules provide an open, porous channel in the horizontal plane[d] (5, 11).
[c] First ply or as vapor barrier under insulation. Coated on both sides with asphalt and surfaced on top side with fine mineral granules (2, 9).
[d] Product does not crack, tear, or cause damage upon being unrolled at 10–60°C.
[e] To convert g/m^2 to lb/100 ft^2, multiply by 0.0205.
[f] To convert kN/m to lbf/in., divide by 0.175.
[g] To convert $\mathrm{ng/(Pa{\cdot}s{\cdot}m^2)}$ to $\mathrm{grain/(h{\cdot}in.{\cdot}Hg{\cdot}ft^2)}$, divide by 5.72.

Table 4. Properties of Roofing and Waterproofing Ply Felts[a] for BUR

	Organic felt, asphalt-saturated[b]		Fiber glass mat, asphalt-impregnated[c]		
Property	Type I	Type II	Type III	Type IV	Type VI
nominal weight, g/m^2[d]	560	1270	474	303	303
felt or mat mass, min, g/m^2[d]	254	488	73	83	93
saturant/asphalt mass, min, g/m^2[d]	303	732	308	146	146
breaking strength, min, kN/m[e]					
with grain	5.25	7.0	3.85	7.70	10.5
across grain	2.63	3.5	3.85	7.70	10.5
pliability radius, mm, pass, at 25°C	12.7	19.1	13	13	13
ash, %	10	10	70–88	70–88	70–88
loss on heating at 105°C, 5 h max, %	4	4			

[a] All are nonsticking upon being unrolled at 10–60°C.
[b] Perforated or nonperforated (1).
[c] Ref. 3.
[d] To convert g/m^2 to lb/100 ft^2, multiply by 0.0205.
[e] To convert kN/m to lbf/in., divide by 0.175.

1.1.3. Cold Applied Coatings/Adhesives

Cold applied BUR applications do not require heating to fluidize the bitumen on the job. Simple application and economical maintenance are primary considerations. Bitumens are liquefied by dissolving in a solvent (cutbacks) or dispersing in water (emulsion). The base cutback can be modified by addition of other components, commonly mineral fillers and fibers, to form specialized coatings (qv). At ordinary temperatures, the solvent or water evaporates and forms an adhesive bond.

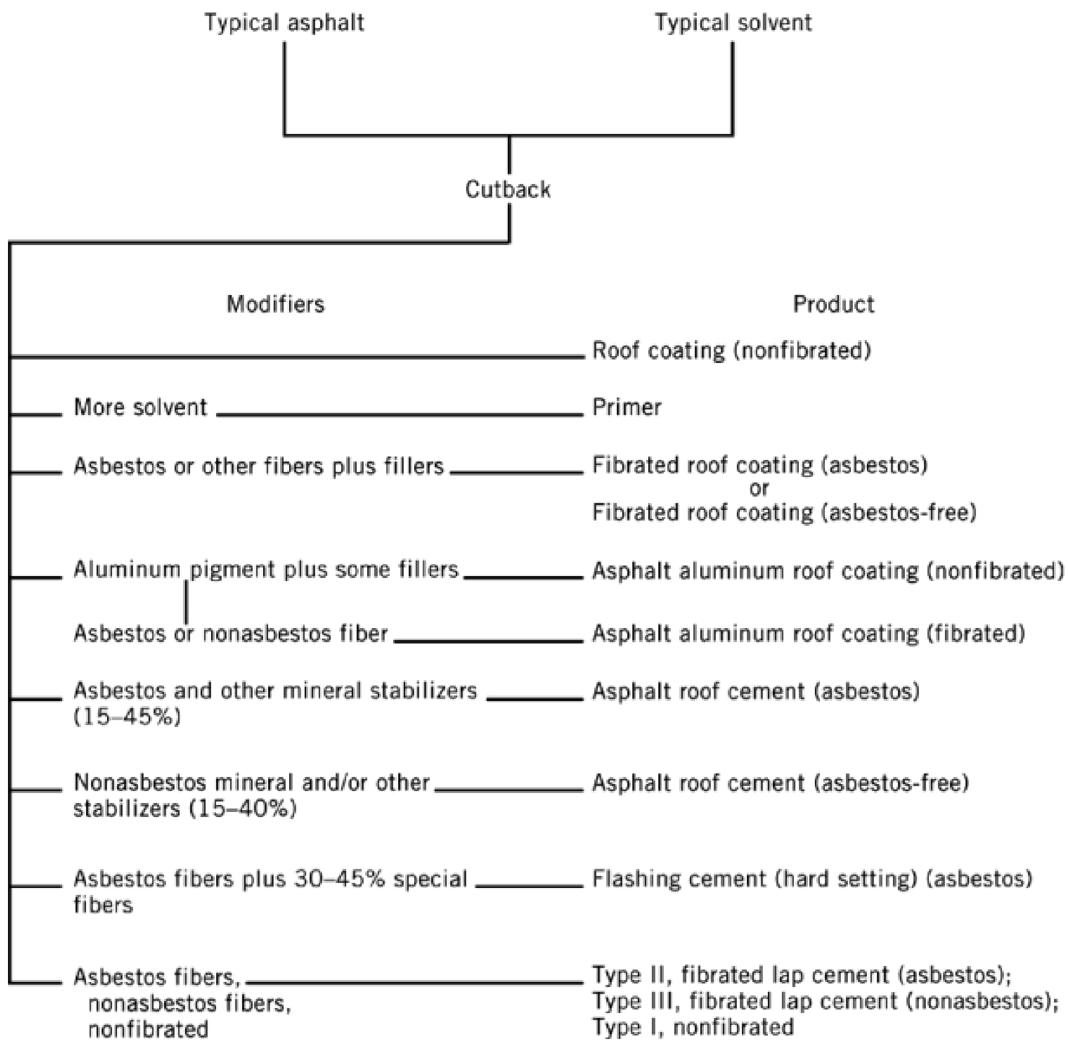

Fig. 1. Production of asphaltic coatings, primers, and cements. Typical asphalt has 18–100 mm penetration at 25°C; typical solvent has a boiling range of 148–210°C. The cutback represents 55–75% asphalt.

The compositions of cold applied coatings/adhesives are illustrated in Figure 1. These coatings range from thin fluids used for priming deck surfaces to viscous mineral-filled compositions used as flashing cements. The ASTM specifications in References 7 and 9–r11 should be consulted for details (see Coatings; Coating processes). Lap cements used with asphalt-roll roofing are specified by ASTM D3019 Type III (14). This specification covers cements consisting of asphalt and petroleum solvent without asbestos. It is an asbestos-free cement.

Emulsified asphalt used as a protective coating is specified by ASTM D1227 (10). These emulsions are applied above freezing by brush, mop, or spray, and bond to either damp or dry surfaces. Such application is not recommended for inclines $<4^\circ$ to avoid the accumulation of water. However, curing by water evaporation can be slow, and these emulsions may remain water-susceptible.

1.2. Protected-Membrane Roofs

Primitive roofs covered with earth and sod over sloping wood decks shingled with bark were early examples of protected-membrane roofs (PMRs). Grass and earth provided insulation and protected the shingled deck from inclement weather.

In modern PMR construction, thermal insulation that is unaffected by water or that can be kept dry in some manner is required. Extruded polystyrene (XEPS) foam insulation boards are commonly employed (see Insulation, thermal). They are placed on top of the waterproofing roof membrane, which is next to the deck. The insulation should not be adhered to the membrane. Ballast at the rate of $\geq$48.8 kg/m^2 (1000 lb/100 ft^2) holds the insulation in place and offers protection from the sun. The insulation joints are open and drainage must be provided. Various other materials, eg, patio blocks and concrete slabs, are also used as surfacings and ballast. The extra weight imposes more exacting requirements on construction.

1.3. Asphalt Roofing Components

Asphalt (qv) is a unique building material which occurs both naturally and as a by-product of crude-oil refining. Because the chemical composition of crude oils differs from source to source, the physical properties of asphalts derived from various crudes also differ. However, these properties can be tailored by further processing to fit the application for which the asphalt will be used. Softening point, ductility, flash point, and viscosity–temperature relationship are only a few of the asphalt properties that are important in the fabrication of roofing products.

Asphalt intended for roofing can be tailored to perform two separate functions. The first is to saturate the organic fiber-based material. This requires that the asphalt be very fluid at processing temperatures so that it can impregnate the base material completely. The second is to coat the saturated roofing to serve as the medium for adhering mineral granule surfacing to the roofing. In the manufacture of roofing on a fiber glass base material, the saturation step is eliminated.

When produced at the refinery, asphalt is soft and sticky and is referred to as flux. Saturants and coating asphalts are both made from the same flux by an oxidizing or dehydrogenation process known as air blowing. During this process, air is bubbled through hot flux. Heat and oxygen cause chemical reactions which increase the molecular weight and carbon:hydrogen ratio, resulting in changed physical properties. Catalysts may be used to produce saturants or coatings that have higher penetration for a given softening point. The blowing process is continually monitored and is completed when the desired properties are produced. The processed asphalt is then pumped to a storage tank prior to delivery to the roofing production line.

At the roofing plant, coating asphalts are blended with mineral stabilizer such as finely ground limestone, slate, flyash, or traprock. The stabilizer increases the coating asphalt's resistance to fire and foot-traffic and adds durability.

1.3.1. Coal-Tar Pitch

Coal tar, a by-product from the coking process of coal for steel production, is also used as a hot-melt adhesive in BURs (see Tar and pitch). When used as ply adhesives, coal tars are generally limited to slopes of 2 cm/m for organic membranes and $<$1 cm/m for glass fiber systems. The permissible slopes for asphalts without nailing range up to 50 cm/m, depending on the asphalt grade specified. Properties of hot applied bitumens for use in BUR as specified by ASTM are given in Tables 5 and 6.

1.3.2. Organic Felts

Roofing felts consist of fiber mats impregnated and/or coated with bitumen. Earlier felts contained rag fiber. Extensive weathering tests and field experience demonstrated that Asplund wood-fiber/recycled paper felts are satisfactory for BUR and prepared roofing without the addition of variable rag fibers. Organic felts are formed by preparing a water slurry of pulp, after which the fibers are picked up by a rotating screened drum

Table 5. Properties of Roofing Asphalt[a]

Property	Type I	Type II	Type III	Type IV
flash point[b], COC[c], °C, min	246	246	246	246
softening point, °C (range)	57–66	70–80	85–96	99–107
slope guideline, max, cm/m	≤2.08	≤8.33	≤25	≤50

[a] Ref. 7.
[b] As of late 1996, ASTM subcommittee D08.03 is considering changing the flash point from 246°C to 260°C.
[c] COC = Cleveland open cup.

Table 6. Coal-Tar Pitch Used in Roofing, Dampproofing, and Waterproofing[a]

Property	Type I	Type II	Type III
flash point, COC[b], °C, min	190	175	205
softening point, ring and ball, °C, max	80	80	

[a] Ref. 13.
[b] COC = Cleveland open cup.

or by a traveling screen. The formed sheet is dried by vacuum suction and steam-heated drums and then calendered and wound into large rolls for subsequent trimming and slitting to the proper width. The organic felt is then saturated by dipping the felt in hot bitumen and passing it over a series of rolls for cooling. The felt is then perforated, marked with guidelines for application, and wound into rolls of convenient size. The small perforations let air and moisture escape during application. Furthermore, the saturant reduces the rate of water vapor absorption. Vapor permeability and water absorption are further reduced by asphalt coatings, stabilized with mineral fillers (qv). A parting agent, eg, sand, talc, or a soap film, is spread on the coating to prevent sticking (see Release agents).

1.3.3. Fiber Glass Felts

Fiber glass felts are manufactured from glass filaments prepared from a molten mixture of silica sodium carbonate, recycled glass, sand, and other ingredients. The filaments may be short (chopped) or continuous. They may be deposited dry or from a dilute water slurry on a screen conveyor. In either process, a binder is applied. Heat is then applied to set the binder. The formed fiber glass mat is then coated with hot asphalt, surfaced with a parting agent (liquid or mineral), cooled, marked with guidelines, and wound into rolls of the desired length. Excellent dimensional stability and low moisture absorption are derived from fiber glass roofing felts. For the production of mineral-surfaced roofing products or shingles, mineral granules are applied to a heavier-coated top side of the felt. Variations in the manufacturing process also produce venting base sheets and flashings. Fiber glass mats are also used to produce modified bitumen roofing products.

1.4. Single-Ply Roofing Membranes

The single-ply roofing membrane category derives its name from the installation technique where a single-ply sheet membrane is applied over the roofing deck/substrate, giving continuous water-tight coverage (15–31). Single-ply has grown from its beginning in the early 1960s to approximately 45% of the low sloped roofing market. There are approximately 16 manufacturers and an additional 20 marketers of these membranes. These flexible membranes offer light weight, excellent chemical and weather resistance, ease of application and repair, and multiple colors. They can be installed in a number of ways, including the traditional fully adhered, the mechanically fastened, and the ballasted roofing systems. They have been designed to comply with various wind and fire code requirements of the construction industry. Because of the light weight of the adhered and mechanically fastened systems, they sometimes can be installed directly over an existing roof system, thus eliminating the waste that would normally be generated from a roof tear-off. Proper precautions should be taken to remove saturated areas of the old roof before overlaying the new system.

As the single-ply industry grew, its influence in the marketplace has increased. The trade association SPRI (Sheet Membrane and Component Suppliers to the Commercial Roofing Industry) was founded to represent the industry on various technical items and to help educate the industry on single-ply. The single-ply industry has also actively pursued the development of standards for the various single-ply products through ASTM and ANSI. These standards cover areas from the performance of a membrane under aging conditions and the endurance of metal components in corrosive environments, to system designs for wind resistance. The standards for membrane materials provide information comparing unaged material with materials after aging for conditions such as ultraviolet radiation, heat aging, water absorption, ozone (qv), cold temperature flexibility, and linear dimensional changes.

There are two basic categories that these flexible membranes fit into: thermoset and thermoplastic. The first is an elastomeric material that undergoes or has undergone a chemical reaction by the action of heat, catalysts, ultraviolet light, etc, leading to a state where the material is infusible and its shape cannot be altered. This chemical reaction, called curing, can occur in the plant or on the roof. The second is a flexible polymeric material that can be softened repeatedly by heating and hardened by cooling through a temperature range characteristic of the plastic. This material in the softened state can be formed or heat-fused to itself.

Single-ply membranes offer the widest range of systems in the roofing industry. The three basic systems are ballasted, fully adhered, and mechanically fastened. From a cost standpoint, the fully adhered system is the most expensive to install, the ballasted system the least. The protected-membrane roofing system can be used with any of the basic systems. The specifications for these systems are published by the various manufacturers. The following gives a brief description of the roof assemblies.

1.4.1. Ballasted

A ballasted roof assembly consists of a membrane or membrane and substrate material (insulation, slip sheet, etc) loosely laid over a deck with the assembly held in place using ballast. A minimum ballast weight of 48.9 kg/m^2 or 10 pounds per square foot (PSF) is used. The ballast can consist of smooth rounded stone, crushed stone (a separator sheet must be used between the crushed stone and the membrane), or pavers (both standard and lightweight). Both stone and pavers come in a wide variety of colors. The membrane is affixed to the building only at the deck perimeter (roof edge) and at various penetrations. Wall and penetration flashings are typically fully adhered and sealed to prevent water entry into the roof assembly. The maximum slope a ballasted system should be installed over is 16.7 cm/m.

Because the ballasted roof uses only 48.8–97.6 kg/m^2 loading, it cannot be evaluated by standard wind uplift test devices such as Factory Mutual's 4470 uplift table or Underwriters' Laboratory's UL 1897 uplift test. Because both devices use air pressure in excess of 146.4 kg/m^2 (30 PSF), the loose ballast would roll off as the membrane inflates. To aid the industry in designing ballasted roof systems for wind, a wind design standard was developed: the ANSI Standard SPRI RP-4: Wind Design Standard for Ballasted Single-Ply Roofing Systems. The standard was developed through wind tunnel work and actual field data documenting the performance of these systems through various wind events, including hurricanes.

1.4.2. Fully Adhered

The substrate, ie, insulation, cover board, etc, that the single-ply membrane is to be attached to is either fully adhered or mechanically fastened to the deck. However, there are also applications where the membrane is adhered directly to the deck. The membrane is then adhered to the substrate. The typical method for adhering the membrane to the substrate is by applying a contact adhesive to the membrane and substrate, rolling the membrane into place, and brooming once the adhesive is ready. There are one-sided applications where the membrane is rolled directly into the adhesive that has been applied to the substrate only. The membrane used in this application method may be fleece-backed. Fully adhered systems can be installed on any slope. The fully adhered application offers a smooth surface that is easy to maintain and inspect, as well as excellent wind resistance on account of positive attachment.

1.4.3. Mechanically Fastened

The substrate, ie, insulation, cover board, etc, which the single-ply membrane must go over, is typically mechanically fastened to the deck using a low density of fasteners. However, there are also applications where the membrane is applied directly to the deck. The typical method of installing a mechanically fastened roof membrane is to lay the membrane over the substrate and fasten it to the deck using fasteners spaced along only one of the machine edges of the sheet. The next sheet is then seamed over the fastener to the first sheet, making the system water-tight with the second sheet's loose edge fastened to the deck. This process continues across the roof deck. The maximum slope normally done with a mechanically fastened roof system is 150 cm/m (18 in. in a foot). For slopes greater than this, special provisions must be made.

There are also mechanically fastened systems where large sheets are laid over the substrate and seamed together. The mechanical fastening system to hold the membrane to the deck is placed at the appropriate density either over the membrane to fasten the system to the deck or under the membrane to which it is affixed.

Mechanically fastening the membrane leaves the membrane loose between the attachment points. This can cause the membrane to billow in strong winds, giving the roof a quilted pillow look. There is nothing functionally wrong with the system, however, there are ways to minimize the billowing by using air barriers, leaving the old roof in place, or using vents. The manufacturer should be consulted as to the best method to control this quilting effect if there is a concern on this factor. As with the fully adhered systems, the mechanically fastened systems offer a smooth surface and excellent wind resistance.

1.4.4. Manufacturing Methods

The single-ply membrane manufacturing process begins with the mixing of the formulation for the sheet. This is where the antioxidants, antiozonants, stabilizers, fire retardants, fillers, reinforcing fillers, plasticizers, and the polymer are mixed together using either an internal batch mixer, where all the ingredients are loaded into a mixer and then discharged when mixed, or through a continuous mixer, where the ingredients are added at specific locations along the mixer, typically an extruder, as the polymer moves through it. The mixed formulation is then processed generally through either a calender consisting of large opposing rolls through which the material passes, or an extruder that forces the material through a die to generate the flat sheet. Two sheets are usually made and laminated together, whether the construction is reinforced or nonreinforced for extra security against any leak. If a hole is made by accident in one sheet, the chances of a hole in the two laminates lining up is basically zero. There are processes where the reinforced sheet is spread or dip-coated to build up the sheet with the polymer coating.

At this point in the process, thermoplastic and chlorosulfonated polyethylene (CSPE) membranes are complete and are ready for packaging. In the case of ethylene–propylene–diene monomer (EPDM), the curing step occurs before the membrane is ready for packaging. The curing process is accomplished by placing the membrane in a large vulcanizer where the material is heated under pressure to complete the cure.

The flexible single-ply membranes are manufactured in three forms: reinforced, nonreinforced, and fleece-back sheet.

1.4.4.1. Reinforced. This is a membrane that has been strengthened by the incorporation of a woven or knitted scrim. This reinforcement is typically a 9-by-9 ends per inch knit or a 10-by-10 ends per inch woven 1000 denier (111 tex) polyester, but other materials, such as fiber glass, can be used. The prime use of reinforced membranes is in mechanically fastened roofing systems where the restriction of the elongation of the polymeric material is important for limiting the billowing of the membrane resulting from wind forces. The membrane is used in other installations, ie, fully adhered and ballasted, when improved puncture resistance is sought. In some applications the reinforcement is part of the manufacturing process as a carrier for the polymer. With some polymeric materials, the reinforcement acts as a stabilizer for the sheet to reduce stresses that can occur on the roof.

1.4.4.2. Nonreinforced. Many nonreinforced elastomeric membranes are available. These allow the roofing system to take full advantage of the elongation, which can be as much as 600%, of the elastomeric membrane. This works to its fullest advantage in handling building movement as well as thermal and other stresses. The nonreinforced membranes are most popular in ballasted roofing systems.

1.4.4.3. Fleece-Back Sheet. A fleece-back sheet is a nonreinforced polymeric membrane that has had a nonwoven mat made of polyester, weighing 101.7–203.4 g/m^2, laminated to the back of the sheet. The prime use of the fleece-back sheet is in the fully adhered roofing systems. The fleece provides the chemical separator, which eliminates the need for an adhesive that is compatible with the specific membrane or a compatible substrate.

1.4.5. Polymeric Materials

The single-ply membranes are made from a wide variety of polymers. The following is a brief description of those polymers and their characteristics. There are three thermosetting-type elastomeric membranes as of this writing (1996): neoprene, CSPE, and EPDM. Neoprene is still used where oil resistance is needed. For instance, Hydrotech uses neoprene flashings, the base of which is hot-set in rubberized asphalt (see Elastomers, synthetic–polychloroprene).

1.4.6. CSPE

Chlorosulfonated polyethylene (CSPE), a synthetic rubber manufactured by DuPont, is marketed under the name Hypalon. It can be produced as a self-curing elastomer designed to cure on the roof. The membrane is typically reinforced with polyester and is available in finished thicknesses of 0.75 to 1.5 mm. Because CSPE exhibits thermoplastic characteristics before it cures, it offers heat-weldable seams. After exposure on the roof, the membrane cures offering the toughness and mechanical set of a thermoset. The normal shelf life of the membrane for maintaining this thermoplastic characteristic is approximately six months. After the membrane is fully cured in the field, conventional adhesives are needed to make repairs.

The prime installation method is mechanically fastened but fully adhered and ballasted applications can also be used. CSPE exhibits strong resistance not only to weathering but also to a broad range of chemicals and pollutants; it is also inherently ozone-resistant. It can be produced in many colors and the sheet widths are typically 5–6.5 ft (1.5–1.65 m). The physical characteristics of a CSPE sheet have been described (17) (see Elastomers, synthetic–chlorosulfonated polyethylene).

1.4.7. EPDM

Ethylene–propylene–diene monomer (EPDM) rubber, the largest segment of the single-ply elastomeric roofing membrane category, comprising 30% of the total low slope roofing market, is an elastomeric compound synthesized from ethylene, propylene, and a small amount of diene monomer. It is generally used in roofing as a cured material, but there are also formulas for products such as EPDM flashing that are designed to cure on the roof. The membrane is typically nonreinforced, allowing for full utilization of its elongation characteristics. However, reinforced membranes are also offered, which are primarily used in mechanically fastened roofing systems. The membrane thicknesses are typically 1.1 and 1.5 mm, but can also run from 1 to 2.2 mm. Because EPDM exhibits thermoset characteristics, the seaming together of two sheets is accomplished by adhesive systems. Adhesive systems consist of cleaners, cleaner primers, and primers used in various combinations with butyl liquid or tape adhesives. Sealants (qv) are added to some adhesive systems for protection and redundancy (see Elastomers, synthetic–ethylene–propylene–diene rubber).

EPDM is by far the most widely used material in the ballasted roofing system construction. Because of EPDM's flexibility, very large sheets of up to 10,000 square feet (929 m^2) can be delivered to the job site in compact rolls that offer reduced labor on the roof in the seaming process. The typical EPDM sheet size used in ballasted systems is 12 by 30 m and 1.1 mm thick. EPDM is also widely used in both the fully adhered and mechanically fastened roofing systems. In these constructions, both 1.1- and 1.5-mm thick material is used with widths from 2.1 to 15 m. A majority of the installations use nonreinforced sheet, although reinforced membrane can also be used in all of the system types. The majority of the reinforced sheets go into mechanically fastened systems.

EPDM membranes are highly resistant to weathering, abrasion, and ozone, as well as a broad range of chemicals. EPDM has excellent low temperature flexibility and excellent resistance to acids, alkalies, and oxygenated solvents such as ketones, esters, and alcohol. However, exposure to aromatic, halogenated, and aliphatic solvents as well as animal fats and vegetable oils should be avoided to prevent swelling and distortion of the membrane. The membrane is offered primarily in black because of superior weathering, but white is also available. The physical characteristics of an EPDM sheet have been described (16).

1.4.7.1. Thermoplastics. There are five elastomeric membranes that are thermoplastic. Two materials, chlorinated polyethylene (CPE) and polyisobutylene (PIB), are relatively obscure. Thermoplastic materials can be either heat-fused or solvent-welded. In contrast to Hypalon and uncured EPDM, this ability to fuse the membranes together remains throughout the life of the material. However, cleaning of the membrane surface after exposure to weather is required. Correct cleaning procedures for specific membranes are available from the individual manufacturer.

1.4.8. CPA

Copolymer alloy membranes (CPAs) are made by alloying high molecular weight polymerics, plasticizers, special stabilizers, biocides, and antioxidants with poly(vinyl chloride) (PVC). The membrane is typically reinforced with polyester and comes in finished thicknesses of 0.75–1.5 mm and widths of 1.5–1.8 m. The primary installation method is mechanically fastened, but some fully adhered systems are also possible. The CPA membranes can exhibit long-term flexibility by alleviating migration of the polymeric plasticizers, and are chemically resistant and compatible with many oils and greases, animal fats, asphalt, and coal-tar pitch. The physical characteristics of a CPA membrane have been described (15).

1.4.9. EIP

These membranes are compounds consisting of ethylene interpolymers (EIP), PVC, stabilizers, pigments (qv), antioxidants, and modifying polymers. Generally reinforced with polyester fabric, EIP membranes are usually 0.81 mm thick and come in sheet widths of 3.05–6.1 m. The main installation method is mechanically fastened. EIP membranes possess good resistance to chemicals and oils and have high tear strength. Many formulations utilizing combinations of ethylene polymers with other basic ingredients may be produced. The sheet is usually white in color. As of this writing (1996), an ASTM committee is working to develop a standard for the EIP membranes.

1.4.10. NBP

These nitrile alloy membranes are compounded from PVC, flexibilized by the addition of butadiene–acrylonitrile copolymers, PVC, and other proprietary ingredients. Typically reinforced with polyester scrim, NBP membranes are 1 mm thick and have a width of 1.5 m. They are predominantly used in mechanically fastened roofing systems. NBP membranes exhibit excellent tear and puncture resistance as well as good weatherability, and remain flexible at low temperatures. They are resistant to most chemicals but are sensitive to aromatic hydrocarbons. The sheet is usually offered in light colors. The physical characteristics of NBP membranes have been described (15).

1.4.11. PVC

Poly(vinyl chloride) (PVC), a very versatile polymer, is manufactured by the polymerization of vinyl chloride monomer, a gaseous substance obtained from the reaction of ethylene with oxygen and hydrochloric acid. In its most basic form, the resin is a relatively hard material that requires the addition of other compounds, commonly plasticizers and stabilizers as well as certain other ingredients, to produce the desired physical properties for roofing use. The membranes come in both reinforced and nonreinforced constructions, but since the 1980s the direction has been toward offering only reinforced membranes. The membrane thickness typically runs from 0.8–1.5 mm and widths typically in the range of 1.5–4.6 m.

The greater portion of PVC is installed in the mechanically fastened roofing system; a lesser portion is installed in fully adhered applications. Although PVC was once heavily used in ballasted roofing systems, there are only a small number installed in the 1990s. Fleece-back membrane is popular in the PVC construction for both fully adhered applications as well as in applications where a separator sheet is needed. PVCs are resistant to various weather conditions, bacterial growth, and industrial chemicals. These membranes are chemically incompatible with bituminous materials. PVCs are offered in a variety of colors. The physical characteristics of a PVC membrane have been described (15).

1.4.12. TPO

Thermoplastic polyolefin (TPO) is made by blending ethylene– propylene polymers with polypropylene. The original method of blending the two polymers was by conventional mixing. A more recent technology is to make the two polymers, ethylene–propylene and polypropylene, in the chemical reactor simultaneously, creating a very homogeneous mixture that offers unique properties compared with the original method. The polymer is formulated with stabilizers, pigments, and antioxidants to obtain the appropriate weathering and physical properties for roofing applications. Because of the polymer's inherent flexibility, no plasticizer is required to obtain a flexible sheet. The sheet comes in both reinforced and nonreinforced constructions. Its thickness ranges from 1.1–1.5 mm; its width runs from 1.8–3.0 m.

TPO membrane is most often used in mechanically fastened roofing systems. The reinforced construction is the preferred membrane. Fully adhered systems are installed using both reinforced and nonreinforced constructions. Some ballasted applications are also utilized which use the nonreinforced membrane. TPO membranes are highly resistant not only to a broad range of chemicals, but also weathering, abrasion, and ozone. In addition, they have good low temperature flexibility and excellent resistance to acids, alkalies, and oxygenated solvents such as ketones, esters, and alcohol. However, exposure to aromatic, halogenated, and aliphatic solvents as well as animal fats and vegetable oils should be avoided to prevent swelling and distortion of the membrane. The membrane is offered in a variety of colors. As of this writing, an ASTM committee is working to develop a standard for the TPO membranes.

1.5. Modified Bitumen Membrane Systems

The third main type of roofing system available is a hybrid between the conventional built-up roofing products and the elastomeric single-membrane materials (26). Modified bituminous membranes were developed in Europe in the mid-1960s and have been in use in the United States since 1975. These products are made by adding a polymer to an asphalt, which then raises the softening point of the mixture, along with fillers and other processing ingredients, to form a waterproofing sheet. These products are primarily reinforced with polyester or fiber glass nonwoven mats. Some products can have both fiber glass and polyester mats to form a more specialized modified bitumen product. Two basic polymers are used to manufacture modified bitumen products: atactic polypropylene (APP) and styrene–butadiene–styrene (SBS) block copolymers.

1.5.1. APP

Atactic polypropylene is a low crystallinity (amorphous) thermoplastic material used in bitumen modification. The thermoplastic nature of the modifier gives the product excellent rheological properties for heat welding with a torch, and increases the softening point from 32.2°C (90°F) to 148.9°C (300°F). APP not only imparts good weatherability to the asphalt blend, but provides greater toughness to the roof membrane. One adverse feature of APP, which softens at temperatures above 148.9°C (300°F), is its brittleness at temperatures below −6.7°C (20°F). This is a concern on buildings in cold climates that experience abnormal amounts of movement or impact from tools or other falling objects.

1.5.2. SBS

The other widely used modifier in asphalt is a block copolymer, styrene–butadiene–styrene. SBS is a thermoplastic rubber that has rheological properties different from those of APP. SBS addition to an asphalt increases the flexibility over a wider temperature range than does APP. SBS-modified asphalt has excellent elongation properties, with reversibility, and remains flexible at temperatures below −23.3°C (-10°F). The addition of SBS to an asphalt can also increase the softening point from 32.2°C (90°F) to 137.8°C (280°F). The modified bitumen products are tested according to ASTM D5147 (32). There is activity in Asphalt Roofing Manufacturers Association (ARMA) and in ASTM to develop standards for both APP and SBS roofing membranes. However, as of 1996, none exist.

2. Steep Roofing Products

Asphalt roofing shingles and related products are classified under three broad groups: shingles, roll roofing, and underlayment (34). Shingles and roll roofing are outer roof coverings, ie, they are exposed to the weather and are designed to withstand the elements. Underlayments are inner roof coverings that provide the necessary protection beneath the exposed roofing materials. Asphalt shingles and roll roofing contain two basic components: (*1*) a base material made of an organic felt or fiber glass mat which serves as the matrix that supports the other components and gives the product the strength to withstand manufacturing, handling, installation, and service conditions; and (*2*) a specially formulated asphalt coating that provides the long-term weatherability and stability under service temperature extremes.

2.1. Shingles

Asphalt shingles (33) are the most common roofing material used in the United States in the 1990s, amounting to more than 80% of all residential roofing products. They are manufactured as strip shingles, laminated (multithickness) shingles, interlocking shingles, and large individual shingles in a variety of weights and colors.

Strip shingles are typically rectangular and may have as many as five cut-outs along the long dimension. Cut-outs separate the shingle tabs, which are exposed to the weather, and give the roof the appearance of being comprised of a larger number of individual units. Strip shingles can also be manufactured without cut-outs to produce a much different appearance. The three-tab shingle is the most common type of strip shingle.

Most of the shingles are available with strips or spots of a factory-applied, self-sealing adhesive, which is a thermoplastic material activated by heat from the sun after the shingle is on the roof. Exposure to the sun's heat bonds each shingle securely to the one below for greater wind resistance. This self-sealing action varies, depending on the geographic location, roof slope, season of the year, and solar orientation.

Weather-resistant mineral granules applied to the top surface of strip shingles during the manufacturing process make possible a wide range of colors. Sand, talc, or mica is applied to the back surface.

Table 7. ASTM Tests and Standards for Asphalt Shingles

ASTM designation	Title
D225[a]	Standard Specification for Asphalt Shingles (Organic Felt) Surfaced with Mineral Granules
D3018[b]	Standard Specification for Class A Asphalt Shingles Surfaced with Mineral Granules
D3462[c]	Standard Specification for Asphalt Shingles Made from Glass Felt and Surfaced with Mineral Granules
D3161[d]	Standard Test Method for Wind Resistance of Asphalt Shingles (Fan-Induced Method)
D228[e]	Standard Test Methods for Asphalt Roll Roofing, Cap Sheets, and Shingles

[a] Asphalt roofing in shingle form; single or multiple thicknesses of organic felt saturated and coated on both sides with asphalt and surfaced on weather side with mineral granules; intended to be applied with exposure to weather ≤ 143 mm (5 5/8 in.), and with headlap ≥ 51 mm (2 in.). Classified as Type I, uniform-, or nonuniform-thickness shingles of any style; Type II, thick butt, square tab, strip shingles; and Type III, uniform- or nonuniform-thickness shingles of any style.
[b] Granule-surfaced asphalt roofing shingles meeting Class A fire test exposure conditions (Test Methods E108); intended to be applied with headlap ≥ 51 mm (2 in.). Values (metric) regarded as standard; values in parentheses for information purposes only. Asphalt shingles are Type I, self-sealing; and Type II, nonself-healing.
[c] Asphalt roofing in shingle form, composed of glass felt or felts impregnated and coated on both sides with asphalt, and surfaced on the weather side with mineral granules; intended to be applied with headlap ≥ 51 mm (2 in.). Must be supplied with a factory-applied self-sealing adhesive or be designed to lock together during installation.
[d] Procedures for testing asphalt shingles resistant to wind blowup/blowoff when applied on low slopes in accordance with manufacturer instructions. Shingles are Type I, factory-applied adhesive (self-sealing shingles); and Type II, lock-type, with mechanically interlocking tabs (ears).
[e] Procedures for physical testing and analyses of roofing and shingles composed of asphalt-saturated or glass fiber felt coated to various extents with asphalt and having coated portion surfaced with powders, laminates, or granules; divided into Type I, single thickness of glass felt coated with asphalt and mineral surfacing (eg, Specifications D2178, D3462, D3672, D3909, and D4601); Type II, single thickness of asphalt-saturated felt coated with asphalt and mineral surfacing (eg, Specifications D224, D225, D249, D2626, and D3672); Type III, similar to Type II, but asphalt-coated and surfaced with mineral granules for part of one side of saturated felt (eg, Specification D371); and Type IV, asphalt roll or shingle roofing formed by laminating ≥ 2 mats, felts, papers, foils, fabrics, or films, as web to transport product (eg, Specification D3018).

The tabs of a strip shingle may be cut either straight or offset to obtain a straight or staggered buttline, respectively. They also may be embossed or built up from a number of laminates of base material to give a three-dimensional effect. Each of these shingle characteristics, ie, staggered buttlines, embossing, and laminate, can be combined in various ways to create textures on the finished roof surface that resemble tile, wood, or slate.

Interlocking shingles are also available and are designed to provide immediate resistance to strong winds. These shingles come in various shapes and have various types of locking designs that provide a mechanical interlock on the roof. Large individual shingles are generally rectangular or hexagonal in shape. Table 7 lists ASTM tests and standards for asphalt shingles.

2.2. Roll Roofing

As the name implies, roll roofing is manufactured, packaged, and shipped in rolls. It comes in a wide range of weights and measures. Roll roofing products are produced by applying an asphalt coating to the reinforcing core, and finished with either a smooth or mineral granule surface. Some mineral-surface roll roofing are manufactured with a granule-free selvage edge that indicates the amount each succeeding course should overlap the preceding course. The manufacturer's recommendations with respect to the top, side, and end laps should be followed. The amount of overlap determines how much of the material is exposed to the weather and the extent of coverage to the roof surface; ie, whether most of the surface has a single or a double layer of roll roofing. In addition to its use as a roof covering, roll roofing is also important as a flashing material. Table 8 lists ASTM designations for roll roofing.

Table 8. ASTM Tests and Standards for Roll Roofing

ASTM Designation	Title
D224[a]	Standard Specification for Smooth-Surfaced Asphalt Roll Roofing (Organic Felt)
D249[b]	Standard Specification for Asphalt Roll Roofing (Organic Felt) Surfaced with Mineral Granules
D371[c]	Standard Specification for Asphalt Roll Roofing (Organic Felt) Surfaced with Mineral Granules (Wide Selvage)

[a] Sheet form, composed of organic roofing felt, saturated with asphalt and coating on both sides with asphalt compound that may or may not contain mineral stabilizer, surfaced with powdered talc, mica, or other fine mineral matter to prevent sticking. Classified, in mineral net mass per unit area of roofing, as Type I, 1943 g/m^2 (39.8 lb/100 ft^2); Type II, 2666 g/m^2 (54.6 lb/100 ft^2); Type III, 2495 g/m^2 (51.1 lb/100 ft^2); and Type IV, 1943 g/m^2 (39.8 lb/100 ft^2).
[b] Sheet form, in widths as agreed upon by purchaser and seller, composed of asphalt-saturated organic felt coated on both sides with asphalt and surfaced on weather side with mineral granules, except for selvage. Classified, in minimum net mass of granule-surfaced portion, as Type I, 3610 gm/m^2 (74.0 lb/100 ft^2); and Type II, 3490 gm/m^2 (71.5 lb/100 ft^2).
[c] Sheet form, 914 mm (36 in.) in width, or widths agreed upon by purchaser and supplier, composed of asphalt-saturated organic felt with approximately half the width of weather side coated with asphalt and surfaced with mineral granules, for use as cap sheet in construction of BUR. Materials covered by this specification, in minimum mass per unit area, are Type I, 1806 g/m^2 (37.0 lb/100 ft^2); Type II, 2260 g/m^2 (46.3 lb/100 ft^2); Type III, 1733 g/m^2 (35.5 lb/100 ft^2); and Type IV, 2090 g/m^2 (42.8 lb/100 ft^2).

Table 9. ASTM Tests and Standards for Saturated Felts

ASTM Designation	Title
D226[a]	Standard Specification for Asphalt-Saturated Organic Felt Used in Roofing and Waterproofing
D4869[b]	Standard Specification for Asphalt-Saturated Organic Felt Shingle Underlayment Used in Roofing

[a] With or without perforations, may be used with asphalts conforming to Specification D312 requirements in construction of BUR, and Specification D449 requirements in membrane system of waterproofing. Felts covered by this specification are Type I (No. 15 asphalt felt); and Type II (No. 30 asphalt felt).
[b] Shingle as underlayment with asphalt shingles. Felts covered by this specification are Type I, shingle underlayment; and Type II, heavy-duty shingle underlayment.

2.3. Saturated Felts and Underlayments

These products consist of a dry felt which may be impregnated or coated with an asphalt saturant. They are used primarily as underlayment for asphalt shingles, roll roofing, and other types of roofing materials. These types of felts are also useful as sheathing paper. Saturated felts are manufactured in a variety of weights for use as underlayment or heavy-duty underlayment. Table 9 lists ASTM designations for saturated felts.

2.4. Specialty Eaves Flashing Membranes

Specialty eaves flashing membranes are polymer-modified bituminous sheet materials that are used as underlayment to resist leakage of shingle roofs as a result of ice dams. These sheet materials contain an adhesive layer which is exposed by removing its protective sheet. Special eaves flashing membranes can also be useful in warmer climates where a similar backup of water can occur from an accumulation of pine needles and leaves.

2.5. Fire Resistance

Asphalt roofing shingles and rolls are tested by independent laboratories in accordance with established fire-resistance standards. The most widely accepted standard for fire resistance in building materials is ASTM E108, Standard Test Methods for Fire Tests of Roof Coverings. If the material meets the standard, the product may carry the testing laboratory's label indicating its class of fire resistance in accordance with the named standard. These classes are Class A, severe exposure to fire; Class B, moderate exposure to fire; and Class

C, light exposure to fire. Most glass fiber-based asphalt roofing shingle products manufactured in the United States carry a Class A rating, although many organic felt shingles carry the Class C rating.

2.6. Wind Resistance

Asphalt shingles are certified to wind performance test standards on a continuous basis through independent third-party testing laboratories. Shingles that have passed the standard wind performance requirements, such as ASTM D3161, Standard Test Method for Wind Resistance for Asphalt Shingles, are identified by labels from the testing laboratory with whom they are in compliance.

2.7. Other Shingle Products

Making up about 20% of the steep market are wood shingles and shakes, concrete and clay tiles, natural and mineral fiber slates, and various styles of metal products (34).

2.7.1. Tile

A versatile product, tile is traced back to ancient Greece, China, and Japan. Tile (35) has high fire resistance and is offered in a variety of textures and styles. Both clay and concrete tiles are relatively heavy and require a more robust structure than those used for asphalt shingles.

2.7.2. Slate

Used for hundreds of years, slate comes from different geographical areas and varies in color and weight. Slate (36) is easily split to size and shape; the most common is 4.76-cm (3/16-in.) thick and can weigh 31.71 kg/m^2 (650 lb/100 ft^2) or more. Imitation products of mineral fiber and cement stimulate its durability and style.

2.7.3. Wood Shingles and Shakes

Early roofs in the United States were primarily hand-split hickory or cypress shakes. The natural beauty and style of these materials make them popular. Fire-retardant treatment and underlays may be needed to meet local fire codes. Wood shingles are sawn cedar having a uniform thickness. Wood shakes are usually hand-split and resawn.

2.7.4. Metal

Metal shingles and stamped panels that imitate wood or tile are available. These are light in weight and come in many colors and styles, from pre-engineered to custom-fabricated.

3. Roofing System Performance

Performance (effectiveness) of a roof covering is determined not only by environmental conditions, but also by the individual components that make up the roofing system. The design should be such that no component is underdesigned, compromising the overall performance. Each component should be durable to contribute to the overall roof performance. Procedures for accelerated testing of an entire roofing system are still in the developmental stage as of the mid-1990s. Most criteria are based on durability tests of components, determination of system design, and the proper combination of the roof elements. Roof coverings are subjected to external abuse, eg, foot or other traffic, in addition to weather exposure. The majority of roof leaks are attributed to the defects at penetrations or flashings, so care must be taken to design and install flashings properly.

3.1. Weathering

Bitumen hardens progressively owing to ultraviolet attack, oxidation reactions, and, to some extent, loss of plasticizing oils, especially with coal tars. Temperature changes cause expansion and contraction of the roof covering. Other weather factors include moisture, ice, and hail. Wind affects shingles as well as BUR membrane performance. In an accelerated weather study of 15 coating-grade asphalts, a sixfold variation in durability was reported. Performance is correlated to properties and composition. Low asphaltene and high resin contents are desirable. As weathering progresses, the brittle-point temperature, taken by the Fraass procedure, increases. Blending of fractions or base stocks from different crudes improves performance more than antioxidants.

In a comprehensive review of theoretical and practical aspects of asphalt durability, six weathering factors were considered. A test apparatus for the accelerated weathering of organic materials and procedures was developed at the U.S. National Institute of Standards and Technology (formerly the National Bureau of Standards); a carbon arc was used as the energy source. However, outdoor weather exposures are standard procedures for prepared roofing. The opaque granules and mineral stabilizers in the coating asphalts offer excellent protection against the destructive effects of radiant energy and, even in the accelerated Weather-o-meter, many daily cycles are required for failure. Finely divided mineral stabilizers affect the weatherability of coating-grade roofing asphalts. Additions up to 60 wt % of mineral additives can increase durability. Platy minerals such as ground slates and mica (qv) are the most effective. The nature of the asphalt, however, is the most important consideration.

A number of laboratory procedures even more rapid than the accelerated Weather-o-meter have been described for the determination of expected weatherability of coating asphalts. Research sponsored by the Asphalt Roofing Manufacturers Association describes a stepwise procedure to determine changes in the crude asphalt source (see Asphalt).

3.2. Thermal Effects

Temperature influences the oxidation rate, whereas temperature changes impart a mechanical stress to roof coverings. Daily temperature changes, sometimes quite abrupt, can result in a fatigue mechanism causing tensile failure. Repeated cycles of straining, especially at a high level, diminish the strength of roofing felts to the rupture point. Strain reduction by partial fixing of the membrane to the deck offers the biggest improvement in performance.

Data for thermal movement of various bitumens and felts and for composite membranes have been given (1). These describe the development of a thermal shock factor based on strength factors and the linear thermal expansion coefficient. Tensile and flexural fatigue tests on roofing membranes were taken at 21 and 18°C, and performance criteria were recommended. A study of four types of fluid-applied roofing membranes under cyclic conditions showed that they could not withstand movements of $\leq$1.0 mm over joints. The limitations of present test methods for new roofing materials, such as prefabricated polymeric and elastomeric sheets and liquid-applied membranes, have also been described (1). For evaluation, both laboratory and field work are needed.

3.3. Water Effects

Water in its different forms, ie, liquid, vapor, hail, and ice, profoundly influences the performance of roof coverings. Moisture migrations through roof insulation, eg, vapor that accumulates and later liquefies or water that leaks through the roof covering, reduces insulating efficiency and leads to physical deterioration of the roofing material. Moisture can be detected by direct cut tests, electrical-resistance moisture meters, ir scanning techniques, or nuclear moisture meters.

Flashing flaws in some roofs can be directly responsible for water leakage. The National Roof Contractors Association (NRCA) has developed criteria for curb and edge detail. The recommended flashings include those for stacks, pipes, and expansion joints. Factory Mutual Systems (FM) prescribe perimeter-flashing details dealing primarily with wind-uplift forces that can be encountered on built-up roofs. Roof edge damage in windstorms can be extensive and may result in loss of the roofing membrane, which leads to rain leakage and interior damage.

In roof coverings, organic felts are highly susceptible to expansion and contraction movements with moisture change. Shingles, with a low degree of asphalt saturation, especially if the felt has not been uniformly saturated, show warping. This is described as fish mouthing or clawing. Erratic movements in built-up roofing can be produced by moisture–thermal effects and may cause ridging and failure of the membrane by cracking.

The absorbed equilibrium moisture content of built-up roofing membranes varies with changing environmental conditions. In faulty designs, moisture accumulates during late fall and winter in amounts exceeding those that the system can accommodate in the summer. The weakening effects of moisture are substantially less on fiber glass membranes that possess low equilibrium moisture contents. Organic felt laminates show more movement owing to humidity changes than to temperature changes. Glass felts show small and moderate dimensional changes in response to humidity and temperature changes, respectively; these changes are essentially nondirectional. Roof coverings should be able to withstand $1\frac{1}{2}$ in. diameter hailstones without damage. Icing is a function of the roof slope, roof covering composition, and amount of sun exposure.

3.4. Fire and Wind Hazards

Weather resistance of roof coverings is not necessarily correlated to fire and wind resistance. Underwriters' Laboratory and the Factory Mutual System test and rate fire and wind hazard resistance, and some durability tests. Organic felt or fiber glass mat base shingles are commonly manufactured to meet minimum UL requirements, which, in addition to minimum mass, require wind and fire resistance properties.

3.5. Fire Ratings

Above-deck fire hazards are rated by following ASTM E108 for propagation of the flame along the surface of the roof covering and on the penetration of the fire into the deck or structure. Surface-burning characteristics are measured by either the spread-of-flame test, for noncombustible decks, or the burning brand and intermittant fire tests for combustible decks. The test deck, with a roofing system applied (either a shingle, BUR, or single-membrane construction), is set at a specific incline or slope and exposed to a standard gas flame or burning brand. A list of classified systems is published by each testing agency.

Metal deck assemblies are tested by UL for under-deck fire hazard by using their steiner tunnel (ASTM E84). The assembly, exposed to an under-deck gas flame, must not allow rapid propagation of the fire down the length of the tunnel. FM uses a calorimeter fire-test chamber to evaluate the hazard of an under-deck fire. The deck is exposed to a gas flame and the rate of heat release is measured and correlated to the rate of flame propagation. A different FM test assesses the damage to roof insulations exposed to radiant heat.

3.6. Wind Testing

UL employs two wind resistance tests, one for shingles and another for BUR assemblies. ASTM D3161 is a standard procedure for measuring the wind resistance of asphalt shingles. In ASTM D3161 and the UL shingle test, the conditioned test deck is placed at a specified slope and exposed to a wind velocity of 97 km/h (60 mph) for two hours or until either failure by tab or shingle lifting is known.

Factory Mutual provides loss prevention data sheets that explain how to protect buildings from wind damage. Pressure coefficients that define increased uplift at corners and edges adjust the calculated uplift pressures. A laboratory uplift pressure test rates roofing assemblies. An uplift pressure of 2.9 kPa (0.42 psi) must be withstood under FM conditions to meet the Class 1-60 requirements. The FM approval guide is revised annually (37).

4. Economic Aspects

The National Roofing Contractor's Association conducted a survey of U.S. contractors' total sales, the type of materials used, the percentage of low slope work performed, and the amount contributed by new construction and reroofing in 1995 (38). In 1995, low slope roofing was estimated to take up 71.9% of the total roofing market, at $13.2 billion, of which 74.9% was dominated by the reroofing segment. According to the survey, the systems most often specified for low slope reroofing and new construction were single plies, eg, EPDM, CSPE, and PVC. These membranes captured 32.7% of the reroofing market and 40.5% of the new construction market. The built-up roofing systems had 26.8% of the reroofing sector and 23.5% of the new construction market. Modified bitumen roof membrane had 23.2% of the reroofing segment and 16.9% of the new construction market. APP and SBS modifieds were equally employed. Sprayed polyurethane foam (SPF) usage for the reroofing and new construction markets was 2.6% and 2.3%, respectively. Liquid-applied systems had 2.2% in reroofing and 0.9% in new construction.

The steep-slope roofing market amounted to 28.1% of the total roofing market, at $5.15 billion in 1995. In the steep-roofing market, 81.3% of the business was reroofing, and new construction accounted for 18.7%. As for reroofing materials, asphalt shingles, which include fiber glass (54.3%) and organic (13.7%), continue to dominate the steep-slope roofing market with a 68% share. Other materials used in the reroofing segment were low slope materials (19.9%), tile (2.6%), metal (2.8%), wood shingles/shakes (2.4%), slate (2%), and other (2.3%). In the new construction market, estimates are made for the following materials used: asphalt shingles (63.1%), low slope materials (18.1%), tile (6.3%), metal (2.6%), wood shingles/shakes (4%), slate (3.5%), and other (2.4%).

5. Health, Safety, and Environmental Factors

The materials used by the roofing industry are constantly being scrutinized for health, safety, and environmental requirements. Because the regulations governing the use of these materials change rapidly, it is difficult to indicate where all of the materials stand. A partial listing of the issues that have appeared from 1980–1995 include the Clean Air Act, fiber glass health, asphalt fumes, volatile organic compounds (VOCs), replacement of chlorinated fluorocarbons (CFCs) by hydrochlorinated fluorocarbons (HCFCs), elimination of asbestos products, and greater emphasis on recycling. This list is only a small sampling of the issues that have surrounded the roofing industry. Any study of this industry should always involve a review of the latest regulations regarding the use of any products.

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