these materials will be covered in Section 1.10 and in Chapter 9. They are indeed viable geosynthetic materials in their own right.

## 1.6 OVERVIEW OF GEOMEMBRANES

### 1.6.1 History

In 1839, Charles Goodyear used vulcanization to cure natural rubber with sulfur, resulting in a synthetic rubber that is the current classification of *thermoset polymers*. The impetus was the inherent instability of natural (gum) rubber—i.e., it was brittle in cold weather and sticky in hot weather. Today, the production of various synthetic rubber materials is a major industry. The original geomembrane was a rubber product and was used as a water reservoir pond liner. It was butyl rubber, which is a copolymer of isobutylene with approximately 2% isoprene. Butyl rubber is quite impermeable and has its major use as inner tubes and as the liners of tubeless tires. Many other combinations and variants of rubber materials are possible—for example, nitrile and EPDM. Since the 1980s, however, the geosynthetics industry has shifted from thermoset polymers to *thermoplastic polymers*, the exception being EPDM geomembranes. Thus, almost all of the geomembrane materials we will discuss fall into the category of polymers classified as thermoplastic materials. By definition, these are materials that become soft and pliable when heated without any substantial change in inherent properties and when cooled revert back to their original properties. Thus they are readily seamed by heat, extrusion, or chemical methods.

Polyethylene is formed by the polymerization of compounds containing an unsaturated bond between two carbon atoms. Production in quantity began in 1943. Its main original uses were (and continue to be) in the packaging and molding industries. In its various densities, polyethylene is the most widely used polymer in the manufacturing of geomembranes. The development of crystallizing polypropylene is an outgrowth of low-pressure polymerization of ethylene and is the basic material from which many geosynthetics are made (recall Figure 1.2). Polyvinyl chloride is another member of this group commonly used to manufacture geopipe and, when plasticized, geomembranes. This resin was developed in 1939 and has extensive uses. It ranks second in use to the various density polyethylenes. It is interesting to note that polyethylene geomembranes were first used in Europe and South Africa and moved to North America, while polyvinyl chloride used for geomembranes had its roots in the United States and moved to Europe and elsewhere. Other types of geomembranes were being developed in the 1960s and were used by the U.S. Bureau of Reclamation. These geomembranes served primarily as canal liners, and their use spread to Canada, Russia, Taiwan, and Europe. Another early geomembrane, chlorosulfonated polyethylene (CSPE), resulting from the reaction of chlorine and sulfur chloride on polyethylene, was introduced for reservoir and landfill liners in the late 1960s. This geomembrane type was used in Europe shortly thereafter. Today's polymeric geomembranes are made from various thermoplastic resins and are manufactured and distributed throughout the world, making all types of products readily available. However, what matters most to the owner/designer/specifier, and what is the focus of this book, is to use the proper material for the particular project. *That* is the essence of the design-by-function concept.

### 1.6.2 Manufacture

The manufacturing of geomembranes begins with the production of the raw materials, which include the polymer resin itself; various additives such as antioxidants, plasticizers, fillers, carbon black; and lubricants (as a processing aid). Recall Table 1.6, which gave the approximate amounts of different materials used to make geosynthetic materials. These raw materials are then processed into geomembrane sheets of various widths and thicknesses by one of the three ways shown in Figure 1.19: (1) extrusion, (2) calendering, and (3) spread coating.

High-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), and flexible polypropylene (fPP) geomembranes are manufactured by an *extrusion* method. The polymer resin in pelletized form is mixed with a pelletized master batch that contains carbon black, stabilizers, and antioxidants in a carrier resin. The two pelletized material systems are carefully metered to result in the proper formulation and pneumatically loaded into the feed hopper of an extruder (see Figure 1.20). The extruder contains a heated rotating continuous flight screw. The formulation passes successively through a feed section, compression section, and metering section where it

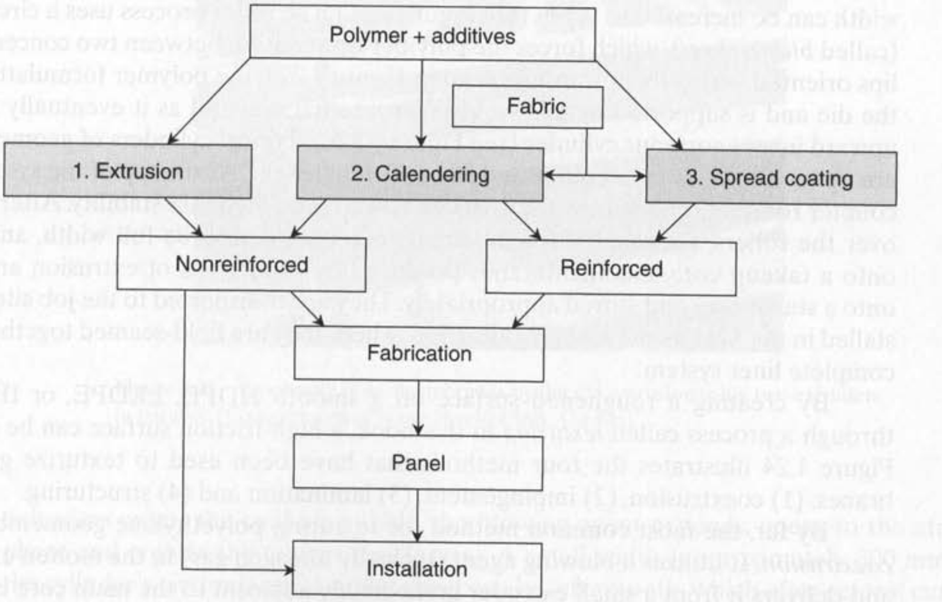


**Figure 1.19** Three methods used to manufacture geomembranes. (After Haxo [39])

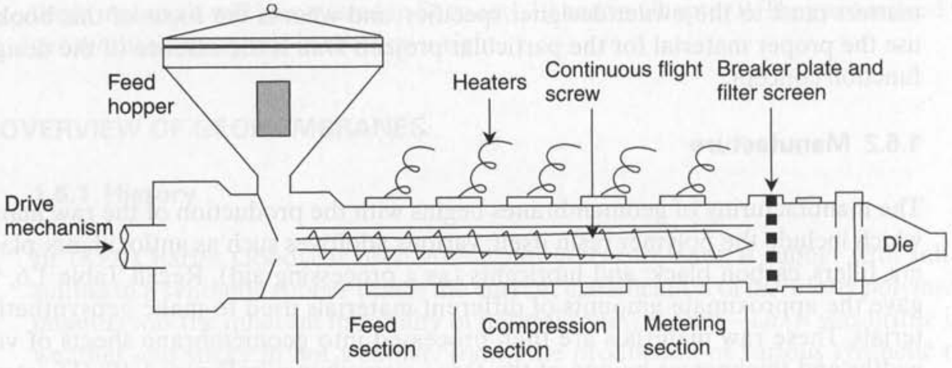
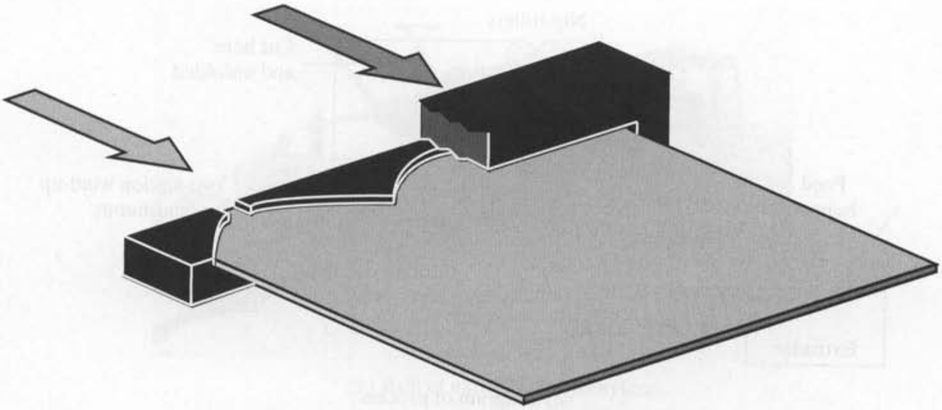


**Figure 1.20** Cross-section diagram of a horizontal single-screw extruder for polymer processing.

finally emerges as a mixed and molten material that is passed through a breaker plate and filter screen and then fed directly into a die. Two variations of extrusion processing are then used to make geomembranes. One process uses a flat die (called *cast sheet*), which forces the polymer formulation between two horizontal die lips, in a coathanger-like manner, resulting in polymer sheet of closely controlled thickness from 0.75 to 3.0 mm. The sheet widths vary from 1.8 to 4.6 m. When two parallel extruders are used, the width can be increased to 9.5 m (see Figure 1.21). The other process uses a circular die (called *blown sheet*), which forces the polymer formulation between two concentric die lips oriented vertically upward. As seen in Figure 1.22a, the polymer formulation exits the die and is supported by a large circular internal mandrel as it eventually extends upward in an enormous cylinder (see Figure 1.22b). Typical cylinders of geomembrane are up to 10 m in circumference and 30 to 40 m in height. At the top of the system, two counter rotating rollers draw the cylinder upward and maintain stability. After passing over the rollers, the sheet is longitudinally cut, unfolded to its full width, and rolled onto a takeup core. Geomembranes produced by both types of extrusion are rolled onto a stable core and stored appropriately. They are transported to the job site and installed in the field as shown in Figure 1.23a, where they are field-seamed together into a complete liner system.

By creating a roughened surface on a smooth HDPE, LLDPE, or fPP sheet through a process called *texturing* in this book, a high-friction surface can be created. Figure 1.24 illustrates the four methods that have been used to texturize geomembranes: (1) coextrusion, (2) impingement, (3) lamination and (4) structuring.

By far, the most common method for texturing polyethylene geomembranes is *coextrusion*. It utilizes a blowing agent (typically nitrogen gas) in the molten extrudate and delivers it from a small extruder immediately adjacent to the main core extruder. When both sides of the sheet are to be textured, two small extruders are used. (For blown film, one internal and one external to the main extruder are needed; for cast sheet, one above and below the main extruder.) As the extrudate from these smaller



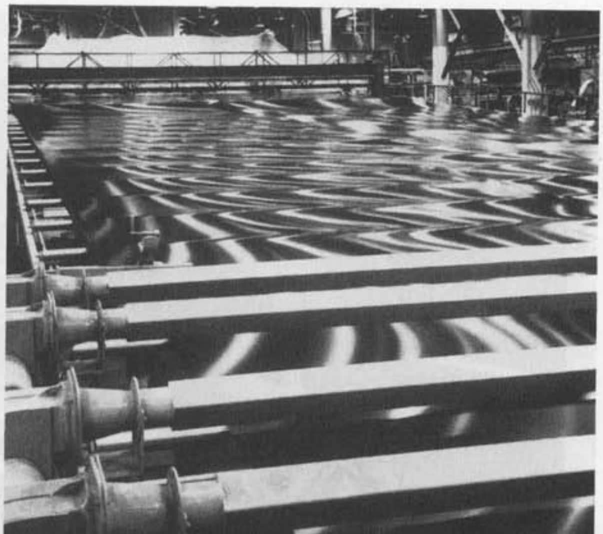
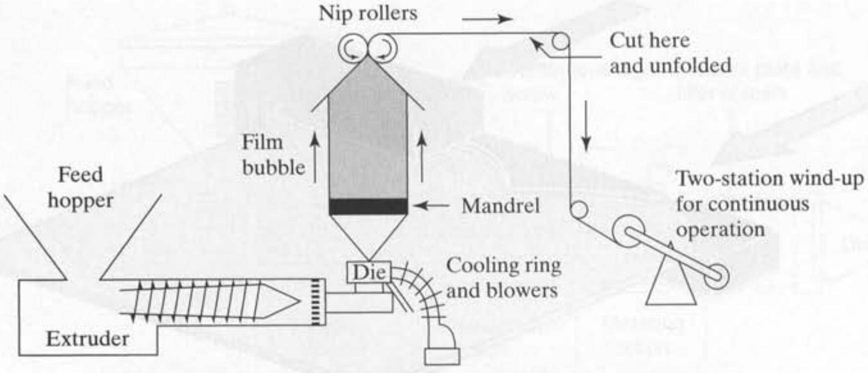


Figure 1.21 Processing of geomembranes by flat die extrusion using two extruders in parallel. (Compliments of Naue Fasertechnik, GmbH)

extruders meets the cool air bubble, the blowing agent expands, opens to the atmosphere and creates the textured surface(s). A small width (approximately 300 mm) of the cylinder's circumference or flat sheet can be left smooth, which after central cutting or trimming, becomes the two lengthwise edges of the roll for ease of seaming.

The second method of texturing is *impingement*, a process in which hot polyethylene particles are actually projected onto the previously manufactured smooth sheet



(a) Diagram of process

(b) Film bubble

**Figure 1.22** Processing of geomembranes by blown sheet extrusion. (Compliments of GSE Lining Technology, Inc.)

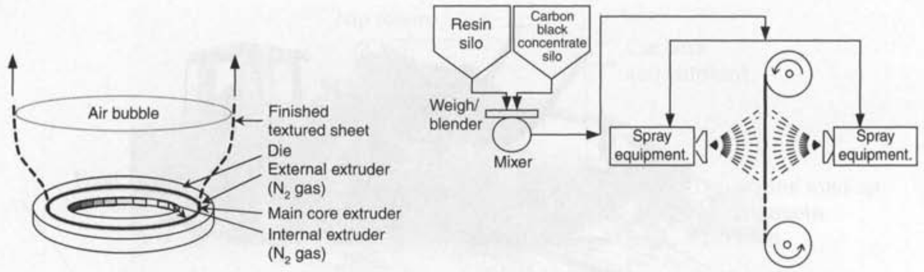
(a) Roll of extruded polyethylene

(b) Accordion-folded pallet of calendered polyvinyl chloride

**Figure 1.23** Geomembranes being deployed in the field.

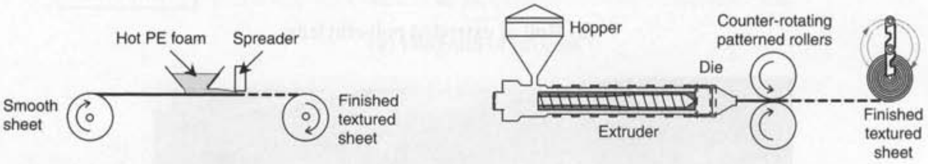
on one or both of its surfaces in a secondary operation. The adhesion of the hot particles to the cold surface(s) should be as great, or greater, than the shear strength of the adjacent soil or other abutting material. The lengthwise edges of the sheets are left nontextured for approximately 150 mm for ease of seaming. The method is common in Europe but not often used in the United States due to its relatively high cost during manufacturing.

The third method of texturing is *lamination*, a process that involves a foam on the previously manufactured smooth sheet in a secondary operation. In this method a foaming agent contained within molten polyethylene provides a froth that is adhered to the previously manufactured smooth sheet providing a rough textured surface. The degree of adhesion is important with respect to the shear strength of the adjacent soil or other abutting material. If texturing on both sides of the geomembrane is necessary, the roll must go through another cycle but now on its opposite side. The lengthwise edges of the sheets are left nontextured for approximately 150 mm so that field-seaming can be readily accomplished. This method is expensive and is rarely used.



(a) Coextrusion with nitrogen gas

(b) Impingement of hot polyethylene particles



(c) Lamination with polyethylene foam

(d) Structuring, or patterning, a surface

**Figure 1.24** The four methods used to produce textured surfaces on HDPE, LLDPE, and fPP geomembranes.

The fourth method of texturing is *structuring*, or *patterning*. In this method a smooth sheet is made by the flat die method and immediately upon leaving the die lips passes between two counter-rotating patterned rollers. These rollers have patterned surface(s) allowing the still hot sheet (approximately at 120°C) to pass between and deform into the inverse pattern of the rollers. This gives a single or multiple raised surface patterns on the sheet as it exits the rollers; the most typical is a box and point pattern, but the variations are endless. For example, the patterned rollers can have a very knurled and rough pattern and the subsequent sheet will reflect the inverse of this pattern. The lengthwise edges of the sheets are left nontextured for approximately 150 mm so that field-seaming can be readily accomplished. This texturing method is a common one, particularly for geomembranes manufactured in Europe.

PVC, CSPE, and scrim-reinforced geomembranes including CSPE-R and fPP-R are not produced as described above and are manufactured by *calendering*, a method in which the polymer resin, carbon black, filler, plasticizer (if any), and additive package are weighed (recall Table 1.6) and mixed in a batch (Banbury-type) or continuous mixer (Farrel-type). During mixing, heat is added, which initiates a reaction between the components. The material exits the mixer and moves by conveyor to a roll mill where it is further blended and homogenized, or "masticated." Now in the form of a continuous mass, it is conveyed through a set of counter-rotating rollers (called a "calender") to form the final sheet. The versatility of calenders is seen in Figure 1.25. This type of manufacturing gives rise to the concept of multiple plies of laminated geomembranes, sometimes with an open-weave fabric (called *scrim*) inserted between the individual plies. The openings in the scrim must be large enough to allow the plies to

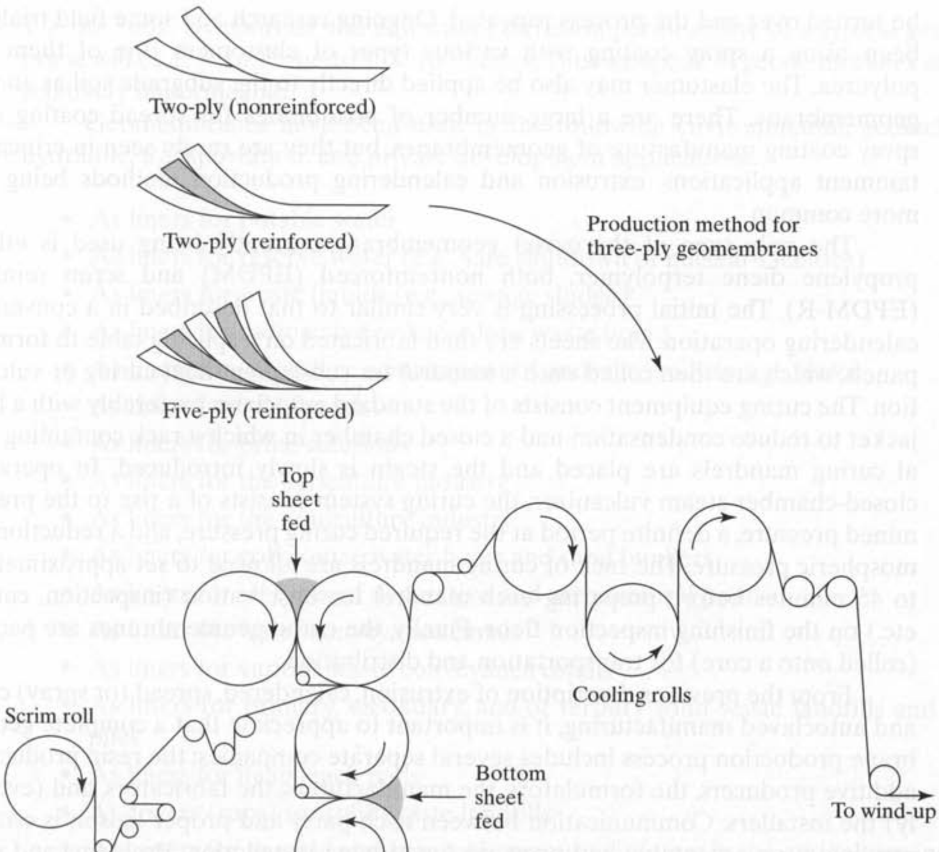


**Figure 1.25** Processing of geomembranes by calendering, utilizing multiple plies of material. (Compliments of JPS Elastomerics, Inc.)

adhere to one another (called "*strike through*") with adequate ply adhesion to prevent delamination. When the fabric scrim is included, geomembranes are called "reinforced" and carry the designation accordingly—for example, CSPE-R or fPP-R. Geomembranes produced by calendering are available in widths of up to 2 to 3 m. To produce much wider widths (called *panels*), the rolls are sent to a fabricator who factory-seams the roll edges together and packages them in a double accordion-folded manner for shipment to the field (see Figure 1.23b).

Reinforced geomembranes can also be made by a manufacturing method called *spread coating*. In this method the molten polymer (whatever its formulation) is spread in a relatively thin coating over a tightly woven fabric or even a nonwoven fabric. Generally, the open pore spaces of the fabric are insufficient to allow for penetration to the opposite side; hence, if coating on both sides of the fabric is required, the material must be turned over and the process repeated. Ongoing research and some field trials have been using a spray coating with various types of elastomers, one of them being polyurea. The elastomer may also be applied directly to the subgrade soil as an in situ geomembrane. There are a large number of possibilities for spread coating and/or spray coating manufacture of geomembranes, but they are rarely seen in critical containment applications, extrusion and calendering production methods being much more common.

The only type of thermoset geomembrane currently being used is ethylene propylene diene terpolymer, both nonreinforced (EPDM) and scrim reinforced (EPDM-R). The initial processing is very similar to that described in a conventional calendering operation. The sheets are then fabricated on a splicing table to form large panels, which are then rolled onto a mandrel for subsequent heat curing or vulcanization. The curing equipment consists of the standard autoclave, preferably with a heated jacket to reduce condensation and a closed chamber in which a rack containing several curing mandrels are placed and the steam is slowly introduced. In operating a closed-chamber steam vulcanizer, the curing system consists of a rise to the predetermined pressure, a definite period at the required curing pressure, and a reduction to atmospheric pressure. The rack of curing mandrels are allowed to set approximately 30 to 45 minutes before preparing each mandrel for observation (inspection, cut plan, etc.) on the finishing/inspection floor. Finally, the cured geomembranes are packaged (rolled onto a core) for transportation and distribution.

From the previous description of extrusion, calendered, spread (or spray) coated, and autoclaved manufacturing, it is important to appreciate that a complete geomembrane production process includes several separate companies: the resin producer, the additive producers, the formulators, the manufacturers, the fabricators, and (eventually) the installers. Communication between each party and proper liaison is critical in arriving at an acceptable and properly functioning installation. Problems and misunderstandings can arise because of the relatively large number of parties involved. It is critical that proper manufacturing quality control (MQC) measures be taken by the manufacturer and fabricator in bringing to the job site the geomembrane that was designed, specified, and purchased. The quality procedures embodied in ISO 9000 and ISO 14,000 indicate to the designer, specifier, and purchaser that a manufacturing quality control (MQC) system has been developed and is being practiced by the manufacturer. In this same light, manufacturing quality assurance (MQA)—seeing that the proper geomembrane has been manufactured per the project plans and specifications—is important and routinely practiced in the geomembrane industry.

### 1.6.3 Current Uses

A wide range of uses of geomembranes have been developed, all of which relate to the primary function of a material being "impermeable." Note at the outset that nothing is *strictly* impermeable in an absolute sense. Here we are speaking of relative impermeability compared to that of competing materials. In the case of solid- or liquid-waste containment geomembranes, the competing material is often natural or amended clay, which usually has a targeted hydraulic conductivity (permeability) of approximately

$1 \times 10^{-9}$ m/s. By contrast, the equivalent diffusion permeability of a typical geomembrane will be $1 \times 10^{-11}$ m/s to $1 \times 10^{-14}$ cm/s. Thus we speak of geomembranes as being relatively impermeable.

Geomembranes have been used in the following environmental, geotechnical, hydraulic, transportation, and private development applications:

- As liners for potable water
- As liners for reserve water (e.g., safe shutdown of nuclear facilities)
- As liners for waste liquids (e.g., sewage sludge)
- As liners for radioactive or hazardous waste liquid
- As liners for secondary containment of underground storage tanks
- As liners for solar ponds
- As liners for brine solutions
- As liners for the agriculture industry
- As liners for the aquiculture industry
- As liners for golf course water holes and sand bunkers
- As liners for all types of decorative and architectural ponds
- As liners for water conveyance canals
- As liners for various waste conveyance canals
- As liners for primary, secondary, and/or tertiary solid-waste landfills and waste piles
- As liners for heap leach pads
- As covers (caps) for solid-waste landfills
- As covers for aerobic and anaerobic manure digesters in the agriculture industry
- As liners for vertical walls: single or double with leak detection
- As cutoffs within zoned earth dams for seepage control
- As linings for emergency spillways
- As waterproofing liners within tunnels and pipelines
- As waterproof facing of earth and rockfill dams
- As waterproof facing for roller compacted concrete dams
- As waterproof facing for masonry and concrete dams
- Within cofferdams for seepage control
- As floating reservoirs for seepage control
- As floating reservoir covers for preventing pollution
- To contain and transport liquids in trucks
- To contain and transport potable water and other liquids in the ocean
- As a barrier to odors from landfills
- As a barrier to vapors (radon, hydrocarbons, etc.) beneath buildings
- To control expansive soils
- To control frost-susceptible soils

- To shield sinkhole-susceptible areas from flowing water
- To prevent infiltration of water in sensitive areas
- To form barrier tubes as dams
- To face structural supports as temporary cofferdams
- To conduct water flow into preferred paths
- Beneath highways to prevent pollution from deicing salts
- Beneath and adjacent to highways to capture hazardous liquid spills
- As containment structures for temporary surcharges
- To aid in establishing uniformity of subsurface compressibility and subsidence
- Beneath asphalt overlays as a waterproofing layer
- To contain seepage losses in existing above-ground tanks
- As flexible forms where loss of material cannot be allowed

### 1.6.4 Sales

Although there are always a few new resins being developed in the geomembrane field, the U. S. market currently is divided between HDPE, LLDPE, fPP, PVC, CSPE-R and EPDM-R and others, such as ethylene interpolymer alloy (EIA-R) and can we summarized as follows:

(Note that $Mm^2$ refers to millions of square meters).

| | |
|---|---|
| High-density polyethylene (HDPE) | $\simeq$40% or 30 $Mm^2$ |
| Linear low-density polyethylene (LLDPE) | $\simeq$25% or 19 $Mm^2$ |
| Polyvinyl chloride (PVC) | $\simeq$20% or 15 $Mm^2$ |
| Chlorosulphonated polyethylene (CSPE) | $\simeq$5% or 4 $Mm^2$ |
| Flexible polypropylene (fPP) | $\simeq$5% or 4 $Mm^2$ |
| Ethylene propylene diene terpolymer (EPDM) | $\simeq$5% or 3 $Mm^2$ |

Data are available for sales of HDPE and LLDPE insofar as various applications and geographic use is concerned. The data for 2002 in millions of kilograms of polymer (Mkg) are shown below.

| Application | HDPE | LLDPE |
|---|---|---|
| Landfill liners | 82.7 Mkg | 4.9 Mkg |
| Landfill covers | 16.5 | 15.2 |
| Liquid impoundments | 16.6 | 2.4 |
| Floating covers | 2.9 | 0.1 |
| Canal liners | 4.6 | 0.1 |
| Secondary containment | 3.9 | 0.2 |
| Heap leach pads | 8.1 | 4.3 |
| Geotechnical uses | 7.9 | 0.2 |
| Total | 143.2 Mkg | 27.4 Mkg |