Zornberg, J.G., and Christopher, B.R. (2007). "Chapter 37: Geosynthetics." In: *The Handbook of Groundwater Engineering*, 2nd Edition, Jacques W. Delleur (Editor-in-Chief), CRC Press, Taylor & Francis Group, Boca Raton, Florida.

37

Geosynthetics

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37.1 Introduction

Geosynthetics can be defined as planar products manufactured from polymeric material, which are used with soil, rock, or other geotechnical engineering-related material as an integral part of a man-made project, structure, or system (ASTM, 1995). Geosynthetics are widely used in many geotechnical, environmental, and hydraulic applications related to groundwater quality and control. One of the most common examples is the use of geotextile filters in trench (i.e., French) drains. Base and cover liner systems for modern landfills also make extensive use of geosynthetics with the main purpose of minimizing the potential for groundwater contamination. Furthermore, the use of geosynthetics is rapidly increasing in applications related directly to groundwater control. This is the case of high density polyethylene (HDPE) vertical barrier systems, which can be used instead of traditional soil-bentonite cutoff walls in projects involving groundwater remediation and control.

The geosynthetics market is strong and rapidly increasing due to the continued use of geosynthetics in well-established applications and, particularly, due to the increasing number of new applications that make use of these products. The strength of the geosynthetics market can be appreciated by evaluating the growth in the estimated amount of geosynthetics in North America over the years. Table 37.1 shows the estimated North American shipments of geosynthetics for 2001. While the total amount of geosynthetics

TABLE 37.1 North American Shipments of Geosynthetics Material 1995–2001 (in million m^2)

	1995	1996	1998	2001
Geotextiles	346.2	356.2	419.7	477.4
Geomembranes	62.4	64.4	74.6	86.8
Geogrids	22.4	24.3	29.1	36.8
Geosynthetic clay liners	5.0	5.4	6.1	8.2
Erosion-control products	72.7	77.8	82.8	93.6
Specialty geosynthetics	16.7	20.1	25.9	31.8

Source: Industrial Fabrics Association International (1996).

produced in North America was slightly over 83 million m^2 in 1980, the production of geosynthetics was approximately 1 billion m^2 in 2005.

Geosynthetics applications are very diverse. To fulfill different functions in the design of geotechnical-, environmental-, and hydraulic-related systems, the geosynthetic industry has developed a number of products to meet engineers' needs. In addition to the use of geotextiles as filters in trench drains, geomembranes in landfill liner systems, and HDPE vertical panels in groundwater control projects, other examples of geosynthetics applications include the use of geotextiles as filtration elements in dams and waste containment systems, the use of geocomposites as erosion control elements in channels and slopes, and the use of geogrids as reinforcement elements in soil embankments, to mention just a few.

Numerous tests have been developed to characterize the hydraulic and mechanical properties of geosynthetics. Many of these properties are important in the manufacture and quality control of geosynthetics; however, many others are also important in design. The material properties that are primarily related to the manufacture and quality control of geosynthetics are generally referred to as index properties and those related to the design are referred to as performance properties. When properly correlated to performance properties, some index properties may also be used for design. As the various geosynthetic products can perform different functions, they should be designed to satisfy minimum criteria to adequately perform these functions in a given design. The different functions performed by geosynthetics are discussed in Section 37.2. The functions that geosynthetics may provide are as follows: separation, reinforcement, filtration, drainage, barrier, and/or protection (or stress relief).

Geosynthetics are manufactured in sheet form in a factory-controlled environment. They are most often packaged in rolls for transporting to the site. They may also be folded or cut and stacked and placed in cartons. At the project site the geosynthetic sheets are unrolled on the prepared subgrade surface, overlapped to form a continuous geosynthetic blanket, and often physically joined to each other, for example, by welding (geomembranes) or sewing (geotextiles). The different types of geosynthetics are discussed in Section 37.3. They include geotextiles, geomembranes, geogrids, geosynthetic clay liners (GCLs), geocomposite sheet drains, geocomposite strip (wick) drains, geocells, erosion control products and HDPE vertical barrier systems.

Different types of geocomposite drains and HDPE vertical barriers, a special form of geomembranes, are considered separately in the list above. These geosynthetics are described separately in this chapter because of their particular relevance in groundwater-related applications.

Geotechnical, environmental, and hydraulic systems frequently incorporate several types of geosynthetics, which are designed to perform more than one function in the system. The bottom and cover liner systems of waste containment facilities are good examples of applications that make use of geosynthetics for multiple purposes. In these facilities, the different geosynthetic products are combined to create the liner system, the components fulfill the functions of infiltration barrier, filtration, separation, drainage, protection, and reinforcement. The multiple uses of geosynthetics in the design of modern landfills are described in Section 37.4. Finally, a case history illustrating the use of HDPE panels as vertical barrier in a groundwater control project is presented in Section 37.5. A glossary of relevant terms and a list of sources are also included for further information.

37.2 Geosynthetic Functions

37.2.1 Design by Function of Geosynthetics

As with other engineering materials, there are several design approaches that could be used during the selection process of geosynthetic products. The most common methods are design by experience, by specification, or by function (Koerner, 2005).

Design-by-experience is generally based on the use of manufacturer's literature and of the designer's experience and familiarity with specific geosynthetic products. An extension of design by experience is design-by-specification, which consists of selecting geosynthetic products for common application areas based on basic minimum or maximum specified property values. These methods may be acceptable for routine, repeat, non-critical applications.

Design-by-function is the preferred approach. Design-by-function should be performed as a check for applications covered by specifications and required for applications not covered by specifications or of such a nature that large property or personal damage would result in the event of a failure. A generic design process that applies to the different geosynthetic functions is summarized as follows (Koerner, 2005):

1. Evaluate the critical and severe nature of the application
2. Determine the function(s) of the geosynthetic
3. Calculate, estimate, or otherwise determine the required property value for the function(s)
4. Test or otherwise obtain the allowable property of the candidate geosynthetic material(s)
5. Calculate the factor of safety (*FS*) as follows:

$$FS = \frac{\text{allowable (test) value}}{\text{required (design) value}} \tag{37.1}$$

6. Determine if the resulting factor of safety is adequate for the site-specific situation under consideration
7. Prepare specifications and construction documents
8. Observe construction and post-construction performance

If the factor of safety is sufficiently high for the specific application, the candidate geosynthetic(s) is (are) deemed acceptable. The same process can be repeated for a number of available geosynthetics, and the final selection among acceptable products is based on availability and cost.

The design-by-function approach is the general approach to be followed in the majority of the projects. As mentioned, the primary function(s) of geosynthetics can be separation, reinforcement, filtration, drainage, infiltration barrier, or protection. However, a certain geosynthetic product can perform different functions and, similarly, the same function can often be performed by different types of geosynthetics. Geosynthetic applications are usually defined by the primary or principal function. In addition, geosynthetics can perform one or more secondary functions, which must also be considered when selecting the geosynthetic characteristics for optimum performance. For example, a geotextile can provide separation of two dissimilar soils (e.g., gravel from clay in a road), but the geosynthetic may also be required to provide the secondary function of filtration to minimize the build up of excess pore water pressure in the soil beneath the separator. The specific function(s) of the different geosynthetic(s) are presented in Table 37.2. Each of these functions is described in Section 37.2.2 to Section 37.2.7.

37.2.2 Separation Function

Separation is the introduction of a flexible, porous geosynthetic product between dissimilar materials so that the integrity and functioning of both materials can remain intact or be improved. For example, a major cause of failure of roadways constructed over soft foundations is contamination of the aggregate base course with the underlying soft subgrade soils (Figure 37.1a). Contamination occurs both due to: (1) penetration of the aggregate into the weak subgrade due to localized bearing capacity failure under

TABLE 37.2 Function of Different Geosynthetic Products

	Geotextile	Geo-membrane	Geogrid	GCL	Geocomposite sheet drain	Geocomposite strip (wick) drain	Geocell	Erosion control product	HDPE vertical barrier
Separation	X	X			X				
Reinforcement	X		X				X		
Filtration	X				X				
Drainage	X				X	X			
Barrier	X[a]	X		X					X
Protection	X			X	X		X	X	

[a]Asphalt-saturated geotextiles.

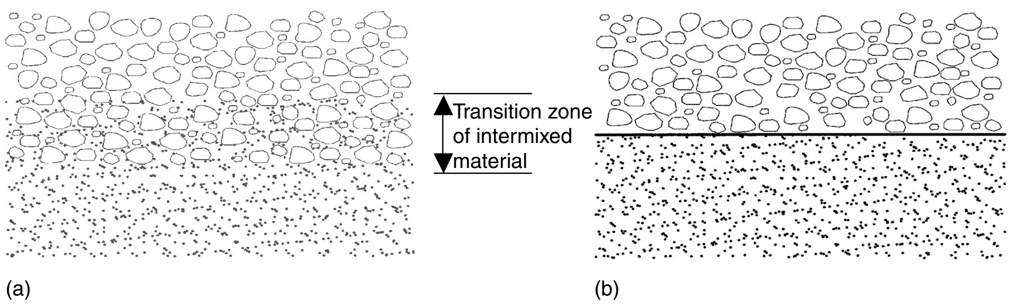

FIGURE 37.1 Separation function of a geotextile placed between road aggregate and soft saturated subgrade. (a) Without geotextile and (b) With geotextile.

stresses induced by wheel loads, and (2) intrusion of fine-grained soils into the aggregate because of pumping or subgrade weakening due to excess pore water pressure. Subgrade contamination results in inadequate structural support that often leads to premature failure of the system. A geotextile can be placed between the aggregate and the subgrade to act as a separator and prevent the subgrade and aggregate base course from mixing (Figure 37.1b).

Among the different geosynthetics, geotextiles have been the products generally used in the function of separation. Examples of separation applications are the use of geotextiles between subgrade and stone base in roads and airfields, and between geomembranes and drainage layers in landfills. In addition to these applications, in which separation is the primary function of the geotextile, it could be said that most other geosynthetic applications generally include separation as a secondary function. The design of geosynthetics for separation applications is provided by Holtz et al. (1997, 1998) and Koerner (2005).

37.2.3 Reinforcement Function

Geosynthetic inclusions within a soil mass can provide a reinforcement function by developing tensile forces that contribute to the stability of the geosynthetic-soil composite (a reinforced soil structure). Design and construction of stable slopes and retaining structures within space constrains are major economical considerations in geotechnical engineering projects. For example, when geometry requirements dictate changes of elevation for a retaining wall, or dam project, the engineer faces a variety of distinct alternatives for designing the required earth structures. Traditional solutions have been either a near vertical concrete structure or a conventional, relatively flat, unreinforced slope (Figure 37.2). Although simple to design, concrete wall alternatives have generally led to elevated construction and material costs. On the other hand, the construction of unreinforced embankments with flat slope angles dictated by stability considerations is an alternative often precluded in projects where design is controlled by space constraints. As shown in

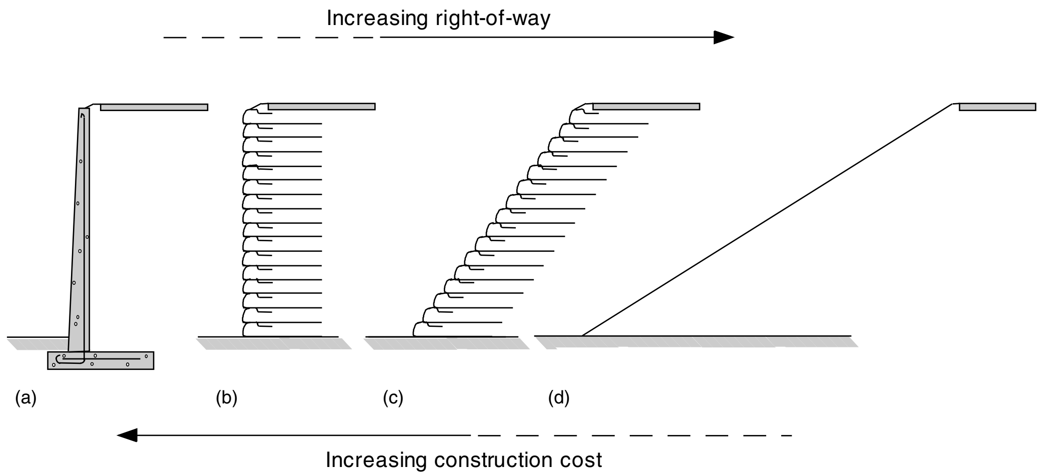

FIGURE 37.2 Reinforcement function of geosynthetics used to optimize the design of earth retaining structures: (a) concrete retaining wall; (b) reinforced wall; (c) reinforced slope; (d) unreinforced slope.

Figure 37.2, an alternative would be to place horizontal, geosynthetic reinforcing elements in the soil to allow construction of very steep embankment side slopes or a vertical reinforced soil wall. For example, vertical reinforced soil walls have been used to both construct dams for reservoirs and increase the height of existing dams.

Geosynthetic products typically used as reinforcement elements are geotextiles and geogrids. Additional products include geocells and fiber reinforcement. Reinforced soil walls generally provide vertical grade separations at a lower cost than traditional concrete walls. Reinforced wall systems involve the use of facing elements such as precast panels, cast-in-place concrete panels, or modular block systems. Alternatively, steepened reinforced slopes (with facing inclination below approximately 70°) may eliminate the use of facing elements, thus saving material costs and construction time in relation to vertical reinforced walls. As indicated in Figure 37.2, a reinforced soil system generally provides an optimized alternative for the design of earth retaining structures by combining lower cost and decreased right-of-way requirements.

The effect of geosynthetic reinforcements on the stability of slopes is illustrated in Figure 37.3, which shows a reduced scale geotextile-reinforced slope model built using dry sand as backfill material. The maximum slope inclination of unreinforced sand under its own weight is the angle of repose of the sand, which is well below the inclination of the slope face of the model in the figure. Horizontal geotextile reinforcements placed within the backfill provided stability to the steep sand slope. In fact, not only did the reinforced slope model not fail under its own weight, but its failure only occurred when the unit weight of the backfill was increased 67 times by placing the model in a geotechnical centrifuge (Zornberg et al., 1998). Figure 37.4 shows the reinforced slope model after centrifuge testing.

The use of inclusions to improve the mechanical properties of soils dates to ancient times. However, it is only within the last 35 years (Vidal, 1969) that analytical and experimental studies have led to the contemporary soil reinforcement techniques. Soil reinforcement is now a highly attractive alternative for embankment and retaining wall projects because of the economic benefits it offers in relation to conventional retaining structures. Its acceptance has also been triggered by a number of technical factors including aesthetics, reliability, simple construction techniques, good seismic performance, and the ability to tolerate large deformations without structural distress. The design of reinforced soil walls is based on earth pressure theory while the design of reinforced slopes is based on the use of limit equilibrium methods. The design process involves evaluation of the external (global), internal, and compound stability of the structure. The required tensile strength of the reinforcements is selected in design so that the margins of safety to prevent internal failure, such as that shown in Figure 37.4, are adequate. Guidance in soil reinforcement design procedures is provided by Elias et al. (2001), Holtz et al. (1997, 1998), and NCMA (1997).

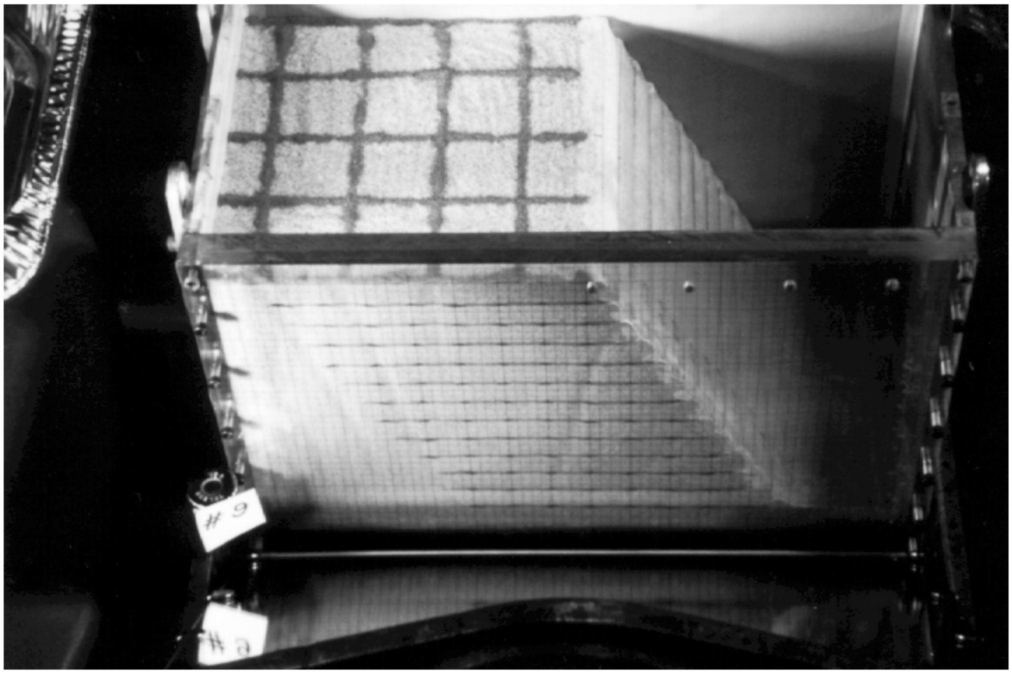

FIGURE 37.3 Model of a sand slope reinforced with geosynthetics.

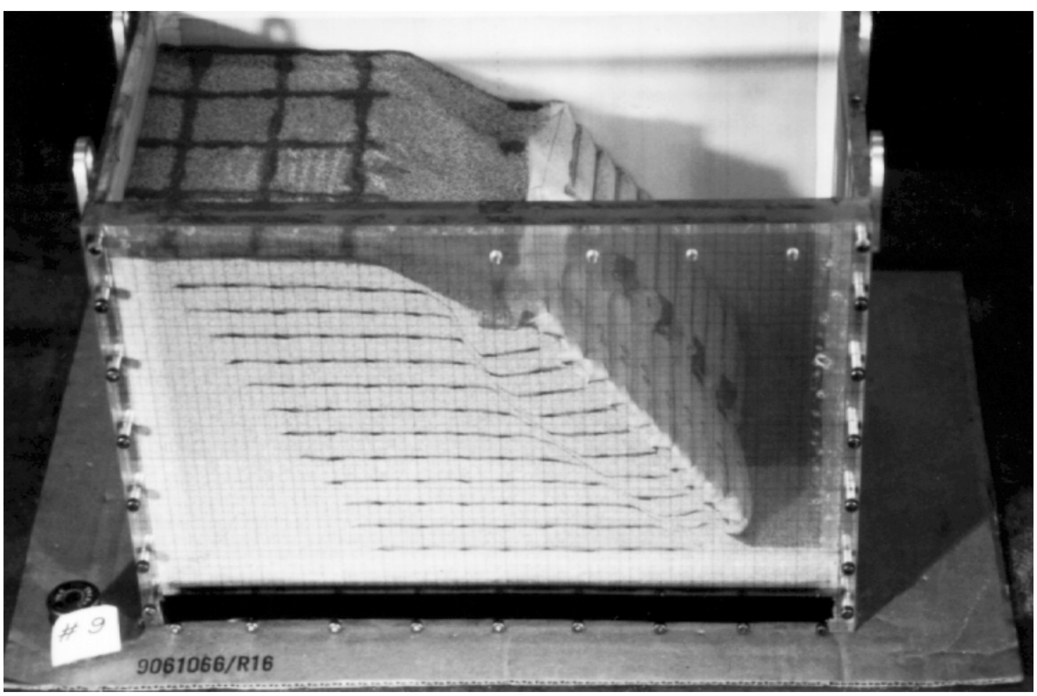

FIGURE 37.4 Reinforced slope model brought to failure by increasing the unit weight of the backfill.

A special form of geosynthetic reinforcement is the mixing of fibers with the soil. Fiber reinforcement is used in applications such as stabilization of thin soil veneers, localized repair of failed slopes and increasing the seismic performance. Randomly distributed fibers can provide isotropic strength increases to the soil and avoid the existence of the potential planes of weakness that can develop on the soil-reinforcement interface. The design of fiber-reinforced soil slopes has typically been performed using composite approaches, where the fiber-reinforced soil is considered as a single homogenized material. Accordingly, fiber-reinforced soil design has required non-conventional laboratory testing of composite fiber-reinforced soil specimens, which has discouraged implementation of fiber-reinforcement in engineering practice. A new discrete approach was recently proposed (Zornberg, 2002), which predicts the "equivalent" shear strength of the fiber-reinforced soil based on the independent properties of fibers (e.g., fiber content, fiber aspect ratio) and soil (e.g., friction angle and cohesion).

37.2.4 Filtration Function

The filtration function involves movement of liquid through the geosynthetic and, at the same time, retention of soil on its upstream side. As indicated in Table 37.2, geotextiles are the product generally used for the function of filtration. Applications include geotextile filters for trench drains, blanket drains, interceptor drains, structural drains, toe drains in dams, filters for hard armor (e.g., rip-rap, gabions, fabric-form) erosion control systems, silt fences, and silt curtains. Both adequate hydraulic conductivity (provided by a geotextile with a relatively porous structure) and adequate soil retention (provided by a geotextile with a relatively tight structure) should be offered by the selected product. In addition, considerations should be made regarding the long-term soil-to-geotextile flow compatibility such that the flow through the geotextile will not be excessively reduced by clogging during the lifetime of the system. The geosynthetic-to-soil system should then achieve an equilibrium that allows for adequate liquid flow with limited soil loss across the geotextile throughout a service lifetime compatible with the application under consideration. Filtration concepts are well established in the design of soil filters, and similar concepts are used in the design of geotextile filters.

As the flow of liquid is perpendicular to the plane of the geosynthetic, filtration refers to the cross-plane hydraulic conductivity. Some of the geosynthetics used for this purpose are relatively thick and compressible. For this reason, geosynthetics are generally characterized by their permittivity, which is defined as:

$$\psi = k_n/t \tag{37.2}$$

where ψ is the permittivity, k_n is the cross-plane hydraulic conductivity, and t is the geosynthetic thickness at a specified normal pressure.

Testing procedures for geotextile permittivity follow similar guidelines used for testing the hydraulic conductivity of the soil. Some designers prefer to work directly with hydraulic conductivity and require the geotextile's hydraulic conductivity to be some multiple of the adjacent soil's hydraulic conductivity (Christopher and Fischer, 1992).

As the flow of liquid through the geotextile increases, the geotextile voids should be larger. However, large geotextile voids can lead to an unacceptable situation called soil piping, in which the soil particles are continuously carried through the geotextile, leaving large soil voids behind. The liquid velocity then increases, which accelerates the process and may lead to the collapse of the soil structure. This process can be prevented by selecting a geotextile with voids small enough to retain the soil on the upstream side of the fabric. It is the coarser soil fraction that must be initially retained. The coarser-sized particles eventually create a filter "bridge," which in turn retains the finer-sized particles, building up a stable upstream soil structure (Figure 37.5).

Several methods have been developed for soil retention design using geotextiles; most of them compare the soil particle size characteristics to the 95% opening size of the geotextile (defined as O_{95} of the geotextile). The test method used in the United States to determine the geotextile opening size is called the apparent opening size (AOS) test (ASTM D 4751).

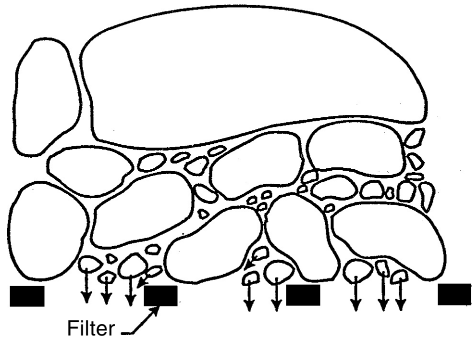

FIGURE 37.5 Geotextile providing adequate filtration through selection of adequate opening size and formation of soil filter bridge.

Some of the soil particles will rest on or embed them within the geotextile structure, and will cause a reduction in the hydraulic conductivity or permittivity of the geotextile. Although some partial clogging should be expected, the designer should ensure that the geotextile will not become excessively clogged, that is, that the flow of liquid will not be decreased to a point in which the system will not adequately perform its function. Thus, the geotextile voids should be large enough to allow the finer soil particles to pass. Clogging potential creates a special problem when geotextiles are used to wrap pipes due to the restricted area available for flow (i.e., a portion of the geotextile is covered by the pipe walls). Any clogging will significantly reduce the flow into the pipe. Either the flow capacity of the geotextile should be increased proportionally to the covered area (i.e., the total pipe area divided by geotextile area available for flow, which is usually the area of the holes in the pipe) or the geotextile should only be used to wrap gravel placed around the pipe. Design guidelines are available for clogging evaluation of non-critical, non-severe cases (Holtz et al., 1997, 1998; Koerner, 2005), but laboratory testing is strongly recommended in important applications. The gradient ratio test (ASTM D 5101), the long-term flow test (Halse et al., 1987), or the hydraulic conductivity ratio test (ASTM D 5567) should be performed. An evaluation of the filtration function of geotextiles is provided by Giroud (1996), Bhatia and Smith (1996a,b), Bhatia et al. (1996), Holtz et al. (1997, 1998), and Palmeira and Fannin (2002).

Proper construction is a critical factor in the performance of the filtration function. To develop and maintain the filter bridge, the geotextile must be placed in continuous (*intimate*) contact with the soil to be filtered such that no void spaces occur behind the geotextile. Placement granular material (e.g., gravel, drain rock, or rip rap) must also be consistent with the strength and durability of the geosynthetic to prevent damage during construction.

37.2.5 Drainage Function

Geosynthetics provide a drainage function by transmitting liquid within the plane of their structure. As shown in Table 37.2, the geosynthetics generally used for drainage purposes are geotextiles and geocomposites. The drainage function of geosynthetics allows for adequate liquid flow with limited soil loss within the plane of the geotextile over a service lifetime compatible with the application under consideration.

Thick, needle-punched nonwoven geotextiles have considerable void space in their structure and can convey liquid in their plane (on the order of 0.01 to 0.1 l/sec/m width of geotextile). Geocomposite drains can transmit one to two orders of magnitude more liquid than geotextiles. Proper design should dictate what type of geosynthetic drainage material is necessary.

The soil retention and the long-term compatibility considerations regarding the drainage function of geosynthetics are the same as those discussed in Section 37.2.4 regarding the filtration function of geosynthetics. As the geosynthetic thickness decreases with increasing normal stress, the in-plane drainage of a geosynthetic is generally quantified by its transmissivity, which is defined as:

$$\theta = k_p \cdot t \tag{37.3}$$

where θ is the transmissivity, k_p is the in-plane hydraulic conductivity, and t is the geosynthetic thickness at a specified normal pressure. The in-plane flow capacity of geosynthetic will reduce under compression and with time (due to creep). Therefore, the transmissivity should be evaluated under normal pressures that are comparable to field conditions with a factor of safety included in the design to account for the design life of the project. Design guidance is provided by Holtz et al. (1997, 1998) and Koerner (2005).

Calculating the thickness of the liquid in or above a liquid collection layer is an important design step because one of the design criteria for a liquid collection layer is that the maximum thickness of the liquid collection layer must be less than an allowable thickness. The thickness of liquid in a liquid collection layer depends on the rate of liquid supply. A typical case of liquid supply is that of liquid impinging onto the liquid collection layer. Two examples of liquid collection layers with such a type of liquid supply can be found in landfills: (1) the drainage layer of the cover system, where the liquid that impinges onto the liquid collection layer is the precipitation water that has percolated through the soil layer overlying the drainage layer; and (2) the leachate collection layer, where the liquid that impinges onto the leachate collection layer is the leachate that has percolated through the waste and through the protective soil layer overlying the leachate collection layer. Equations are available (Giroud et al., 2000) to calculate the maximum thickness of liquid in a liquid collection layer located on a single slope with a perfect drain at the toe.

37.2.6 Barrier Function

The barrier function can be performed by geosynthetic products that have adequately low hydraulic conductivity as to provide containment to liquid or vapor. As shown in Table 37.2, the barrier function may be provided by several types of geosynthetics, namely, geomembranes and geosynthetic clay liners (GCLs). Other geosynthetic products also used as infiltration barriers include membrane-encapsulated soil layers (MESLs) used with paved or unpaved road construction, asphalt-saturated geotextiles used in the prevention of bituminous pavement crack reflection problems, and geofoam used for insulation against moisture and extreme temperatures.

Geosynthetic barriers are commonly used as liner for surface impoundments storing hazardous and nonhazardous liquids, as covers above the liquid surface of storage reservoirs, and as liner for canals used to convey water or chemicals. Geosynthetic barriers are also used as secondary containment for underground storage tanks, and in applications related to dams and tunnels. Of particular relevance for groundwater applications is the use of geosynthetic barriers for seepage control (HDPE vertical barrier systems). A common application of geosynthetics as infiltration barriers is base and cover liners for landfills. In landfill applications, infiltration barriers are typically used instead of (or in addition to) low-hydraulic conductivity soils. Base liners are placed below the waste to prevent liquids from the landfill (leachate) contaminating the underlying ground and the groundwater. Geosynthetic cover liner systems are placed above the final waste configuration to keep precipitation water from entering the waste and generating leachate. If a building or other structure is constructed on a landfill, a geosynthetic barrier may be placed under the building foundation to provide a barrier for vapors such as landfill gas. The use of geosynthetics in infiltration barriers is further described in Koerner (2005).

Dams are among the most critical hydraulic structures and stand to benefit the most from the use of geosynthetics. Deterioration and structural damage due to seepage are major concerns that have been addressed by placement of geomembrane liners. Geosynthetic systems as hydraulic barriers in dams are effective solutions to the problem of degradation. Accordingly, geosynthetics have been used in a wide range of dam types and dam sizes. The first installation of a geomembrane in a dam was in Italy in 1959. Since then, geosynthetics have been installed in dams worldwide as part of new projects and rehabilitation projects. Most recently, the Olivenhain Dam in San Diego was built with a geosynthetic system as an infiltration barrier. Significant advances have taken place in geosynthetics engineering since geomembranes were first used in hydraulic structures. A good example is the current confidence on the extended service life of geomembranes. Additional information on the use of geosynthetics in dams is provided by and can be found in Christopher and Dahlstrand (1989), Zornberg and Weber (2003), Zornberg (2005), and Scuero et al. (2005).

37.2.7 Protection Function

Geosynthetics (mainly geotextiles) can be used to provide stress relief and protect other materials such as geosynthetics (mainly geomembranes) against damage. A common example is the use of geotextiles to provide protection against puncture of geomembranes in waste and liquid containment systems. Adequate mechanical protection must be provided to resist both short-term equipment loads and long-term loads imparted by the waste. Experience has shown that geotextiles can play an important role in the successful installation and long-term performance of geomembranes by acting as a cushion to prevent puncture damage of the geomembrane. In the case of landfill base liners, geotextiles can be placed (1) below the geomembrane to resist puncture and wear due to abrasion caused by sharp-edged rocks in the subgrade, and (2) above the geomembrane to resist puncture caused either by the drainage aggregate or direct contact with waste materials. In the case of landfill cover liners, geotextiles can be placed below the geomembrane to reduce risk of damage by sharp objects in the landfill and above the geomembrane to prevent damage during placement of drainage aggregate or cover soil. Key characteristics for the geotextile cushions are polymer type, mass density, method of manufacture, and construction survivability. The selection process of a geotextile that fulfills a protective function of a geomembrane involves the following three steps: (1) selection of polymer type and method of manufacture; (2) evaluation of the geotextile's capacity to provide puncture protection for the geomembrane; and (3) evaluation of construction survivability. Detailed procedures and methods for conducting these evaluations are described by Holtz et al. (1997, 1998), Koerner (2005), Narejo et al. (1996), and Wilson-Fahmy et al. (1996).

Another protection application associated with groundwater is erosion control blankets and mats. In this case, the geosynthetic protects the ground surface from the prevailing atmospheric conditions (i.e., wind, rain, snow, etc.). Specialty geocomposites have been developed for the specific purpose of erosion control. The general goal of these products is to protect soil slopes from both sheet and gully erosion, either permanently or until vegetation is established. Information on the design of geosynthetics for separation applications is provided by Holtz et al. (1997, 1998) and Koerner (2005).

37.3 Geosynthetic Types

As indicated in the introduction Section 37.1, there are a number of different geosynthetics. The characteristics of these materials vary considerably, primarily due to the method of manufacturing and the types and amount of polymers used for their production. This section provides a brief description of these materials and their primary characteristics. Additional information on the manufacturing process and characteristics of geosynthetics is provided by Koerner (2005) and Holtz et al. (1997, 1998) as well as by manufacturer's organizations, such as the Geosynthetic Manufacturer's Association (www.gmanow.com) and the PVC Geomembrane Institute (pgi-tp.ce.uiuc.edu).

37.3.1 Geotextiles

Among the different geosynthetic products, geotextiles are the ones that present the widest range of properties. They can be used to fulfill all the different functions listed in Table 2.2 for many different geotechnical, environmental, and hydraulic applications. For example, Figure 37.6 shows the construction of a reinforced slope in which geotextiles were selected as multipurpose inclusions within the fill, as they can provide not only the required tensile strength (reinforcement function), but also the required transmissivity (drainage function), needed for that particular project (Zornberg et al., 1995).

FIGURE 37.6 Placement of a high-strength nonwoven geotextile to perform a dual function of reinforcement and in-plane drainage in a reinforced slope.

Geotextiles are manufactured from polymer fibers or filaments that are later formed to develop the final product. Approximately 85% of the geotextiles used today are based on polypropylene resin. An additional 10% are polyester and the remaining 5% is a range of polymers including polyethylene, nylon, and other resins used for specialty purposes. As with all geosynthetics, however, the base resin has various additives, such as for ultraviolet light protection and long-term oxidative stability.

The most common types of fibers or filaments used in the manufacture of geotextiles are monofilament, multifilament, staple filament, and slit-film. If fibers are twisted or spun together, they are known as a yarn. Monofilaments are created by extruding the molten polymer through an apparatus containing small-diameter holes. The extruded polymer strings are then cooled and stretched to give the filament increased strength. Staple filaments are also manufactured by extruding the molten polymer; however, the extruded filaments are cut into 25- to 100- mm portions. The staple filaments or fibers may then be spun into longer yarns. Slit-film filaments are manufactured by either extruding or blowing a film of a continuous sheet of polymer and cutting it into filaments by knives or lanced air jets. Slit-film filaments have a flat, rectangular cross-section instead of the circular cross-section shown by the monofilament and staple filaments.

The filaments, fibers, or yarns are formed into geotextiles using either woven or nonwoven methods. Figure 37.7 shows a number of typical woven and nonwoven geotextiles. Woven geotextiles are manufactured using traditional weaving methods and a variety of weave types. Nonwoven geotextiles are manufactured by placing and orienting the filaments or fibers onto a conveyor belt, which are subsequently bonded by needle punching or by melt bonding. The needle-punching process consists of pushing numerous barbed needles through the fiber web. The fibers are thus mechanically interlocked into a stable configuration. As the name implies, the heat (or melt) bonding process consists of melting and pressurizing the fibers together.

Common terminology associated with geotextiles includes machine direction, cross machine direction, and selvage. Machine direction refers to the direction in the plane of fabric in line with the direction of

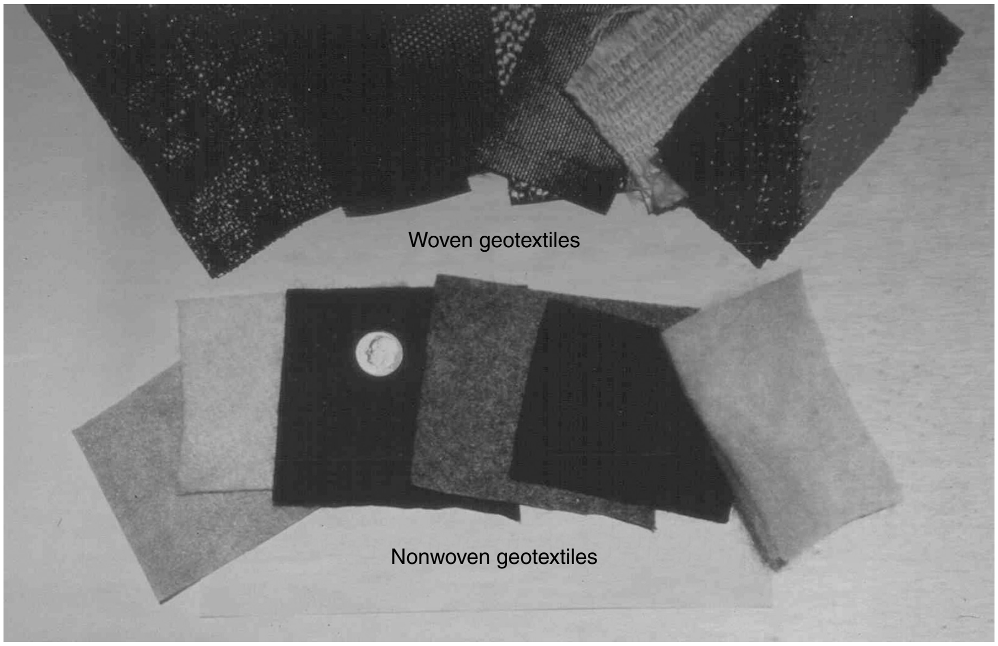

FIGURE 37.7 Typical woven and nonwoven geotextiles.

manufacture. Conversely, cross machine direction refers to the direction in the plane of fabric perpendicular to the direction of manufacture. The selvage is the finished area on the sides of the geotextile width that prevents the yarns from unraveling. Adjacent rolls of geotextiles are seamed in the field by either overlapping or sewing. Sewing is generally the case for geotextiles used as filters in landfill applications, but may be waived for geotextiles used in separation. Heat bonding may also be used for joining geotextiles used in filtration and separation applications.

Numerous tests have been developed to evaluate the properties of geotextiles. In developing geotextile specifications, it is important that the designer understands the material tests and that material properties important for the geotextile's intended use are specified. Table 37.3 describes the tests commonly performed in geotextile products (ASTM, 1995). Geotextiles can generally be specified with index and performance properties. As previously discussed, critical filtration applications are exceptions and the use of pre-qualified specific products from performance flow tests are strongly recommended.

37.3.2 Geomembranes

Geomembranes are flexible, polymeric sheets that have very low hydraulic conductivity (typically less than 10^{-11} cm/sec) and, consequently, are used as liquid or vapor barriers. The most common types of geomembranes are high density polyethylene (HDPE), very flexible polyethylene (VFPE), polyvinyl chloride (PVC), flexible polypropylene (fPP) and reinforced chlorosulfonated polyethylene (CSPE). Figure 37.8 shows a number of geomembranes currently available in the geosynthetics market.

Polyethylene is the type of geomembrane most commonly used in landfill applications for base and cover liner systems. This is primarily because of its high chemical resistance and durability. Specifically, high-density polyethylene (HDPE) is typically used in base liner systems. This material is somewhat rigid but generally has good physical properties and can withstand large stresses often imposed on the geomembrane during construction.

VFPE and PVC are the most commonly used geomembrane materials besides HDPE. The term VFPE encompasses various polyethylene grades such as very low density polyethylene (VLDPE) and certain types of linear low density polyethylene (LLDPE). The linear structure and lack of long-chain branching

TABLE 37.3 Standard Tests for Geotextiles

Property	Test standard	Test name
Thickness	ASTM D 5199	Standard Test Method for Measuring Nominal Thickness of Geotextiles and Geomembranes
Mass per Unit Area	ASTM D 5261	Standard Test Method for Measuring Mass per Unit area of Geotextiles
Grab rupture	ASTM D 4632	Standard Test Method for Breaking Load and Elongation of Geotextiles (Grab Method)
Uniaxial tensile strength geotextiles	ASTM D 4595	Standard Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method
Geogrids	ASTM D 6637	Standard Test Method for Determining Tensile Properties of Geogrids by the Single or Multi-Rib Tensile Method
Multiaxial tensile, puncture or burst tests	ASTM D 6241	Standard Test Method for the Static Puncture Strength of Geotextiles and Geotextile Related Products Using a 50-Mm Probe
Trapezoid tear strength	ASTM D 4533	Standard Test Method for Trapezoid Tearing Strength of Geotextiles
Apparent opening size	ASTM D 4751	Standard Test Method for Determining Apparent Opening Size of a Geotextile
Permittivity	ASTM D 4491	Standard Test Methods for Water Permeability of Geotextiles by Permittivity
Gradient ratio	ASTM D 5101	Standard Test Method for Measuring the Soil-Geotextile System Clogging Potential by the Gradient Ratio
Transmissivity	ASTM D 4716	Standard Test Method for Constant Head Hydraulic Transmissivity (In-Plane Flow) of Geotextiles and Geotextile Related Products
Ultraviolet resistance	ASTM D 4355	Standard Test Method for Deterioration of Geotextiles from Exposure to Ultraviolet Light and Water (Xenon-Arc Type Apparatus)
Seam strength	ASTM D 1683	Failure in Sewn Seams of Woven Fabrics
Seam strength	ASTM D 4884	Standard Test Method for Seam Strength of Sewn Geotextiles

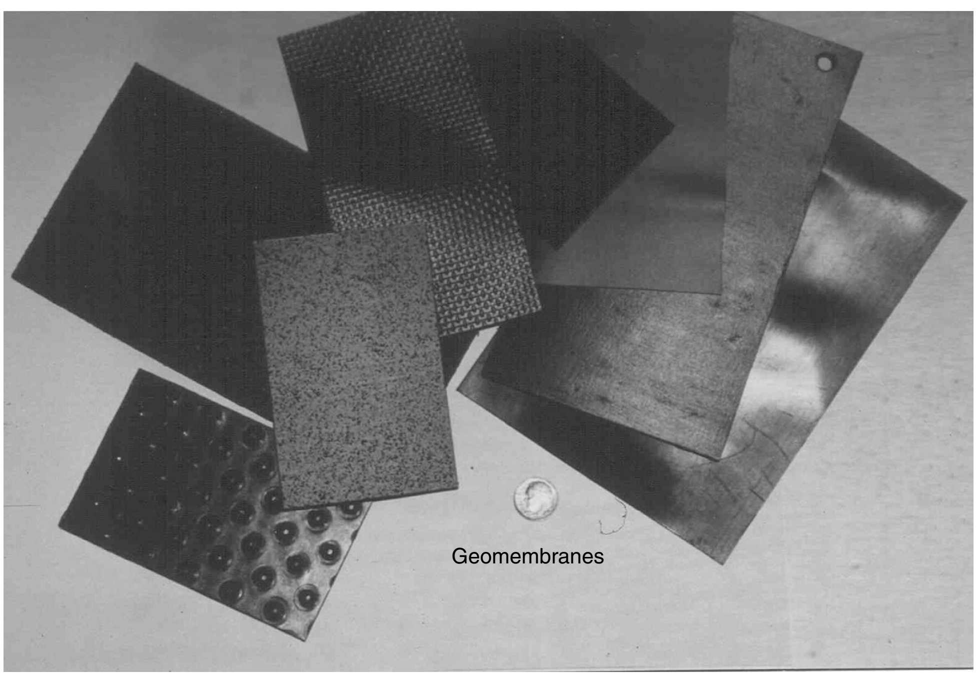

FIGURE 37.8 Typical geomembranes.

TABLE 37.4 Criteria for Selection of HDPE, PVC, or CSPE Geomembranes

Criteria	Considerations for selection
Liquid barrier	All three polymers have acceptable characteristics as liquid barriers, although HDPE geomembranes have the best characteristics in terms of chemical resistance and long-term durability. All three have extremely low hydraulic conductivity and are impermeable for practical purposes.
Mechanical properties	Although the mechanical properties vary somewhat with geomembrane thickness, HDPE is relatively stiff and has relatively small yield strain. PVC, in contrast, is relatively extensible and does not exhibit yield. The tensile properties of CSPE often fall between those of HDPE and PVC but are difficult to generalize because CSPE is usually made with embedded reinforcing fabrics which affect tensile response.
Construction survivability	All three polymers have an acceptable ability to maintain integrity when subjected to concentrated stresses. However, the best performance is obtained with more extensible geomembranes. Therefore, based on the relative extensibility, PVC generally offers the most favorable performance.
Installation	Key considerations include ease of placement and seaming. PVC and CSPE are easier to place than HDPE because their greater flexibility makes them conform more easily to the foundation and makes them less prone to thermal expansion wrinkles. Acceptable placement and wrinkle control, however, can be achieved with all three polymers if appropriate installation procedures are used. All three polymers are easily seamed, with HDPE usually achieving the highest seam strength and quality.
Chemical resistance	HDPE has the highest degree of compatibility with a wide variety of chemicals encountered in wastes. CSPE has good resistance to many chemicals, but is attacked by some that are relatively common, namely chlorinated solvents and hydrocarbons. PVC typically is the least chemically resistant of these polymers.
Long-term durability	HDPE offers the best performance. HDPE is a highly inert and durable material that is not susceptible to chemical degradation under conditions generally encountered in landfills. In addition, HDPE is not susceptible to physical degradation (extraction). The durability of PVC geomembranes is less favorable than that of HDPE. This is because PVC geomembranes are composed of approximately two-thirds PVC resin and one-third plasticizers. Over time, physical degradation (extraction) may cause plasticizer loss which results in reduced geomembrane flexibility. The durability of CSPE geomembranes is typically between that of HDPE and PVC.

in both LLDPE and VLDPE arise from their similar polymerization mechanisms. Due to the large settlements that may occur, cover liner systems commonly require a flexible geomembrane. VFPE is often used in this application as it provides similar chemical resistance as HDPE but is more flexible and can more readily conform to underlying refuse settlements without puncturing. Flexible polypropylene (fPP) geomembranes have recently (1990) been developed by combining the polypropylene (PP) and the ethylene propylene elastomer (EPE). This product was developed to obtain physical characteristics similar to the low density polyethylene while offering the flexibility similar to the polyvinyl chloride geomembranes.

PVC geomembranes are used in liners for many waste containment applications, such as contaminated soils containment and liquid storage ponds. While PVC may not be as durable as polyethylene geomembranes, the merits of PVC geomembranes are that they are generally less expensive than polyethylene geomembrane and can be factory manufactured in relatively large panels. The large panel sizes allow easier installation as there are fewer field fabricated seams.

In landfill applications, geomembranes are typically used as a base or a cover liner in place of or in addition to low-hydraulic conductivity soils. The key performance factors related to the selection of geomembrane polymer types for landfill applications are summarized in Table 37.4. Geomembrane thickness ranges from 0.75 to 2.5 mm (30 to 100 mils). Table 37.5 summarizes the key performance factors related to

TABLE 37.5 Criteria for Minimum Thickness of HDPE Geomembrane

Criteria	Considerations for selection of thickness
Abrasion resistance	The abrasion resistance of HDPE geomembranes increases with geomembrane thickness. Experience indicates that geomembranes with thickness < 1 mm may not have acceptable abrasion resistance.
Response to differential settlements	The thicker the HDPE geomembrane, the higher its stiffness. This issue is more significant for geomembrane cover systems than for geomembrane base liner systems because the cover system must be flexible enough to accommodate differential settlements. From this viewpoint, a thickness of not more than 2 mm is desirable.
Effective welding	The thinner the HDPE geomembrane, the more difficult is the welding of adjacent panels. For most effective welding, a desirable thickness is of at least 1 mm (40 mils), and preferably 1.5 to 2 mm.

the selection of the thickness of HDPE geomembranes for landfill applications. Geomembranes are placed after subgrade preparation, and placement is followed by seaming, inspection, and backfilling. A properly designed geomembrane has the potential of hundreds of years of service lifetime, but installation must follow high quality management principles. In the early uses of geomembranes for waste containment applications, the main concerns were related to the chemical compatibility between geomembranes and waste, and to the service life of geomembranes. Now, construction quality issues are viewed as the principal limitations to the performance of geomembranes.

For continuity of the impermeable barrier, geomembranes should be seamed in the field. The fundamental mechanism of seaming polymeric geomembrane sheets together is to temporarily reorganize (melt) the polymer structure of the two surfaces to be joined in a controlled manner. This reorganization can be done either through thermal or chemical processes. These processes may involve the addition of extra polymer in the bonded area. There are four general categories of seaming methods: extrusion welding, thermal fusion or melt bonding, chemical fusion, and adhesive seaming. Thermal fusion and extrusion welding are the methods most commonly used, and are described next.

In thermal fusion or melt bonding (the most common seaming method), portions of the opposing surfaces are truly melted. Temperature, pressure, and seaming rate play important roles as excessive melting weakens the geomembrane and inadequate melting results in low seam strength. The hot wedge, or hot shoe, method consists of an electrically heated resistance element in the shape of a wedge that travels between the two sheets to be seamed. A standard hot wedge creates a single uniform width seam, while a dual hot wedge (or "split" wedge) forms two parallel seams with a uniform unbonded space between them. This space can then be conveniently used to evaluate seam quality and continuity by pressurizing the unbonded space with air and monitoring any drop in pressure that may signify a leak in the seam (Figure 37.9).

Extrusion welding is at present used exclusively on geomembranes made from polyethylene. A ribbon of molten polymer is extruded over the edge of, or in between, the two surfaces to be joined. The molten extrudate causes the surface of the sheets to become hot and melt, after which the entire mass cools and bonds together. The technique is called extrusion fillet seaming when the extrudate is placed over the leading edge of the seam, and is called extrusion flat seaming when the extrudate is placed between the two sheets to be joined. Fillet extrusion seaming is essentially the only practical method for seaming polyethylene geomembrane patches, for seaming in poorly accessible areas such as sump bottoms and around pipes, and for seaming of extremely short seam lengths.

The material properties of geomembranes are divided into the properties of the raw polymer or resin used in the manufacture of the geomembrane sheet and the manufactured geomembrane properties. Table 37.6 lists the tests commonly performed for evaluation of the raw polymer properties. Table 37.7 summarizes the tests commonly performed to evaluate the manufactured geomembrane sheet properties (ASTM, 1995). As with the geotextiles, many of these tests provide index or quality control properties.

FIGURE 37.9 Monitoring seaming of a geomembrane liner.

TABLE 37.6 Tests for Raw Geomembrane Polymers

Property	Test standard	Test name
Density	ASTM D 792	Standard Test Method for Specific Gravity and Density of Plastics by the Density-Gradient Technique
Density	ASTM D 1505	Standard Test Method for Density of Plastics by the Density-Gradient Technique
Melt index	ASTM D 1238	Standard Test Method for Flow Rates of Thermoplastics by Extrusion Plastometer
Chemical identification methods (fingerprinting)		Thermogravimetric Analysis (TGA) Differential Scanning Calorimetry (DSC) Thermomechanical Analysis (TMA) Infrared Spectroscopy (IR) Chromatography (GC) Gel Permeation Chromatography (GPC)

37.3.3 Geogrids

Geogrids constitute a category of geosynthetics designed preliminary to fulfill a reinforcement function. Geogrids have a uniformly distributed array of apertures between their longitudinal and transverse elements. The apertures allow direct contact between soil particles on either side of the installed sheet, thereby increasing the interaction between the geogrid and the backfill soil.

Geogrids are composed of polypropylene, polyethylene, polyester, or coated polyester. They are formed by several different methods. The coated polyester geogrids are typically woven or knitted. Coating is generally performed using PVC or acrylics to protect the filaments from construction damage and to maintain the grid structure. The polypropylene geogrids are either extruded or punched sheet drawn, and polyethylene geogrids are exclusively punched sheet drawn. Figure 37.10 shows a number of typical geogrid products. In the past several years, geogrids have also been manufactured by interlacing polypropylene or polyester strips together and welding them at their cross-over points (i.e., junctions).

TABLE 37.7 Standard Tests for Geomembranes

Property	Test standard	Test name
Thickness	ASTM D 5199	Standard Test Method for Measuring Nominal Thickness of Geotextiles and Geomembranes
Tensile behavior	ASTM D 6693	Test Method for Determining Tensile Properties of Nonreinforced Polyethylene and Nonreinforced Flexible Polypropylene Geomembranes
Tensile behavior	ASTM D 7003	Test Method for Strip Tensile Properties of Reinforced Geomembranes
Tensile behavior	ASTM D 882	Test Methods for Tensile Properties of Thin Plastic Sheeting (Method A Used for PVC)
Tensile behavior	ASTM D 4885	Standard Test Method for Determining Performance Strength of Geomembranes by the Wide Strip Tensile Method
Tear resistance	ASTM D 1004	Test Method for Initial Tear Resistance of Plastic Film and Sheeting
Puncture resistance	ASTM D 2065	Puncture Resistance and Elongation Test
Puncture resistance	ASTM D 5494	Test Method for the Determination of Pyramid Puncture Resistance of Unprotected and Protected Geomembranes
Puncture resistance	ASTM D 5514	Test Method for Large-Scale Hydrostatic Puncture Testing of Geosynthetics
Environmental stress crack	ASTM D 1693	Standard Test Method for Environmental Stress-Cracking of Ethylene Plastics
Environmental stress crack	ASTM D 5397	Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test
Carbon black	ASTM D 1603	Standard Test Method for Carbon Black in Olefin Plastics
Carbon black	ASTM D 5596	Standard Practice for Microscopic Evaluation of the Dispersion of Carbon Black in Polyolefin Geosynthetics
Durability	ASTM D 5721	Practice for Air-Oven Aging of Polyolefin Geomembranes
chemical resistance	ASTM D 5747	Practice for Tests to Evaluate the Chemical Resistance of Geomembranes to Liquids
Seam strength	ASTM D 4437	Standard Practice for Determining the Integrity of Field Seams Used in Joining Flexible Polymeric Sheet Geomembranes
Leak detection	ASTM D 7007	Practices for Electrical Methods for Locating Leaks in Geomembranes Covered with Water or Earth Materials

Although geogrids are used primarily for reinforcement, some products are used for asphalt overlay and some are combined with other geosynthetics to be used in water proofing or in separation and stabilization applications. In waste containment systems, geogrids may be used to support a lining system over a weak subgrade or to support final landfill cover soils on steep refuse slopes. Geogrids are also used for support of liners in the design of "piggyback" landfills, which are landfills built vertically over older, usually unlined landfills. Regulatory agencies often require that a liner system be installed between the old and new landfill. As the old refuse is highly compressible, it provides a poor base for the new lining system. A geogrid may be used to support the lining system and bridge over voids that may occur beneath the liner as the underlying refuse components decompose.

As with other geosynthetics, geogrids have several physical, mechanical, and durability properties. Many of the test methods used for geotextiles and geomembranes also apply to geogrids. In particular, a key design parameter for reinforcement is the tensile strength, which is performed with the specimen width incorporating typically a few ribs of the geogrid. The allowable tensile strength of geogrids (and of other geosynthetics used for soil reinforcement applications) is typically significantly less than its ultimate tensile strength. The allowable tensile strength is determined by dividing the ultimate tensile strength by partial factors to account for installation damage, creep deformation, chemical degradation, and biological degradation. The partial factors for installation damage, chemical degradation, and biological degradation range from 1.0 to 1.6, with the partial factor of safety for creep ranging from 1.5 to 3.5 (Koerner, 2005). The design engineer should review all recommendations, available codes, national evaluations, and the like and determine appropriate partial factors for the specific projects (i.e., manufacturers' recommendations should be carefully evaluated based on project-specific requirements and not blindly accepted).

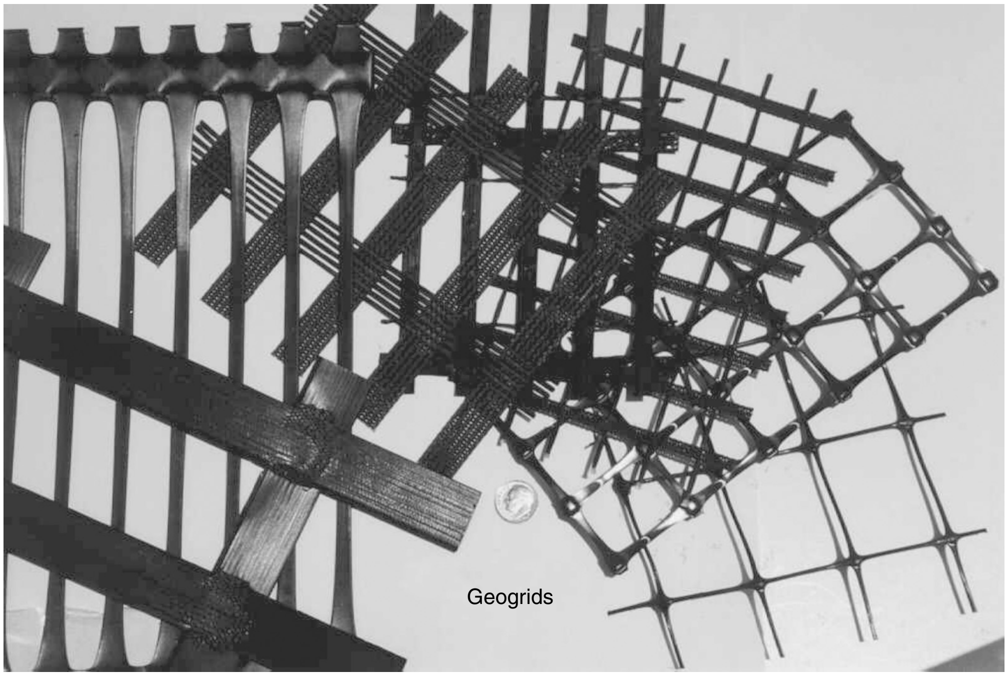

FIGURE 37.10 Typical geogrids.

37.3.4 Geosynthetic Clay Liners

Geosynthetic clay liners (GCLs) are rapidly expanding products in the geosynthetics market. GCLs are infiltration barriers consisting of a layer of unhydrated, loose granular or powdered bentonite placed between two or on top of one geosynthetic layer (geotextile or geomembrane). GCLs are produced in panels that are joined in the field by overlapping. They are generally used as an alternative to compacted clay liners (Bouazza, 2002).

Due to the inherent low shear strength of hydrated bentonite, GCL usage had initially been limited to applications where stability of the overlying materials was not a concern. In the late 1980s, however, methods were developed to reinforce the GCLs, producing a composite material with higher shear strength properties. This allowed the use of GCLs in landfill applications (Figure 37.11).

Some advantages of GCLs over compacted clay liner are that they occupy significantly less space to achieve equivalent performance, plus they are flexible, self-healing, and easy to install. In locations where low hydraulic conductivity clays are not readily available, they may offer significant construction cost savings. In addition, as they are factory manufactured with good quality control, field construction quality assurance costs are typically less than with compacted clay liners.

Bentonite is a clay formed primarily from the mineral montmorillonite. While several types of montmorillonite exist, including calcium and sodium montmorillonite, the term bentonite typically refers to a sodium montmorillonite. Water is strongly attracted to the surface of the negatively charged montmorillonite crystal and is readily absorbed by it. In its unhydrated state, the montmorillonite crystals are densely packed. Once hydrated, the structure becomes very open and swells. The high water absorption and swell characteristics of bentonite lead to its low hydraulic conductivity and low hydrated shear strength.

Geosynthetic clay liners are manufactured by laying down a layer of dry bentonite, approximately 5 mm thick, on a geosynthetic material and attaching the bentonite to the geosynthetic. Two general configurations are currently employed in commercial processes (Figure 37.12): bentonite sandwiched between two geotextiles or bentonite glued to a geomembrane. The primary purpose of the geosynthetic component

FIGURE 37.11 Installation of a GCL during construction of a landfill base liner.

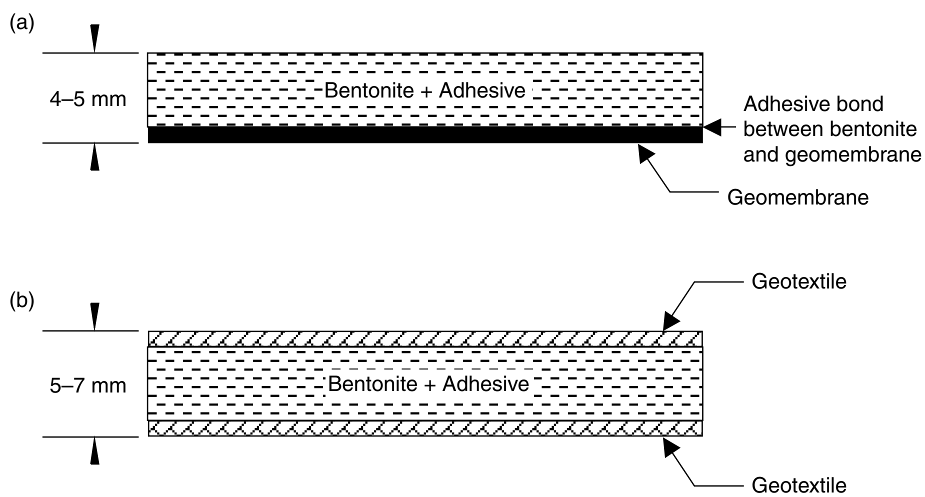

FIGURE 37.12 GCL configurations: (a) bentonite glued to a geomembrane; (b) bentonite sandwiched between two geotextiles.

is to hold the bentonite together in a uniform layer and to permit transportation and installation of the GCL without loss of bentonite.

The outer geosynthetic layer of GCLs can be mechanically bonded using stitching or needle punching (resulting in reinforced GCLs). A different process consists in using an adhesive bond to glue the bentonite to the geosynthetic (resulting in unreinforced GCLs). The mechanical bonding of reinforced GCLs increases their internal shear strength. Geosynthetic clay liners contain approximately 5 kg/m^2 of bentonite that has a hydraulic conductivity of approximately 1×10^{-9} cm/sec. Infiltration under unit hydraulic gradient through a material with hydraulic conductivity of 1×10^{-9} cm/sec would result in an infiltration rate of 0.3 mm per year.

As a GCL is a composite material, its relevant properties are those of the geotextile alone, of the bentonite alone, and of the composite. Geotextile properties were discussed in Section 37.3.1. The geotextile properties relevant to GCLs include mass per unit area, grab tensile, wide-width tensile, and puncture resistance. Relevant properties of the bentonite are obtained from free swell tests, which measure the absorption of water into a bentonite based on its volume change, and plate water absorption tests, which measure the ability of powdered bentonite to absorb water. The relevant properties of the composite GCL material include bentonite content, which is simply a measure of the mass of bentonite per unit area of GCL, permeameter testing (ASTM D 5084) used to estimate the GCL hydraulic conductivity, tensile strength characterized either by grab tensile or wide-width tensile tests, and puncture resistance tests performed to assess the relative puncture resistance between GCLs and geomembranes or other geosynthetics. The internal and interface shear strength of GCLs should also be determined as stability is a major concern for side slopes in bottom liner or cover systems that include GCLs. This is because of the very low shear strength of hydrated sodium bentonite. Proper shear strength characterization is needed for the different materials and interfaces in hydraulic barriers (Koerner, 2005). The analysis of a large database of test results on the internal shear strength of GCLs is presented by Zornberg et al. (2005).

37.3.5 Geocomposite Sheet Drains

A geocomposite consists of a combination of different types of geosynthetics. In particular, the geosynthetics industry has developed a number of geocomposite drains, which are polymeric drainage cores with continuously open flow channels sandwiched between geotextile filters. Geocomposite sheet drains are discussed in this section while geocomposite strip (wick) drains are discussed in Section 37.3.6.

Geocomposite sheet drainage systems have been engineered to replace costly aggregate and perforated pipe subsurface drainage systems. They have reached rapid acceptance because they provide adequate drainage and reduce the material cost, installation time, and design complexity of conventional aggregate systems.

The core of geocomposite sheet drains are extruded sheets of plastic formed into a configuration that promotes drainage. The core of the geocomposite sheet drains are most commonly composed of polyethylene but may also be composed of polypropylene, polystyrene, high-impact polystyrene, or other materials. The structure of the core drainage products ranges from a dimpled core to a geonet. Geonets, a commonly used drainage product, generally consist of two or three sets of parallel solid or foamed extruded ribs that intersect at a constant angle to form an open net configuration. Channels are formed between the ribs to convey either liquid or gases. Figure 37.13 shows a number of geonets currently available in the market. Dimpled cores type products tend to have a greater flow capacity than geonets; however, they generally have a much lower crush resistance and tend to be more compressible than geonets. As indicated in Section 37.2.5, the transmissivity of the geocomposite drain must be evaluated under anticipated site-specific normal pressures and a factor of safety included to account for creep of the product over the life of the system (Koerner, 2005).

The geotextile serves as both a separator and a filter, and the geonet or built-up core serves as a drain. There may be geotextiles on both the top and bottom of the drainage core and they may be different from one another. For example, the lower geotextile may be a thick needlepunched nonwoven geotextile used as a protection material for the underlying geomembrane, while the top geotextile may be a thinner nonwoven or woven product. Composite drainage nets are typically formed by thermally bonding the geotextile and geonet. Gluing and solvent welding can also be used to bond the geosynthetic core to the geotextile. In producing geocomposite drainage nets, the melt temperatures of the geotextile and geonet must be compatible so that the properties of each material are retained. Figure 37.14 shows a number of available geocomposite sheet drainage materials.

As the purpose of the core is drainage, the most important properties to include in specifications are thickness, crush strength, and long-term transmissivity under load. Table 37.8 summarizes the tests

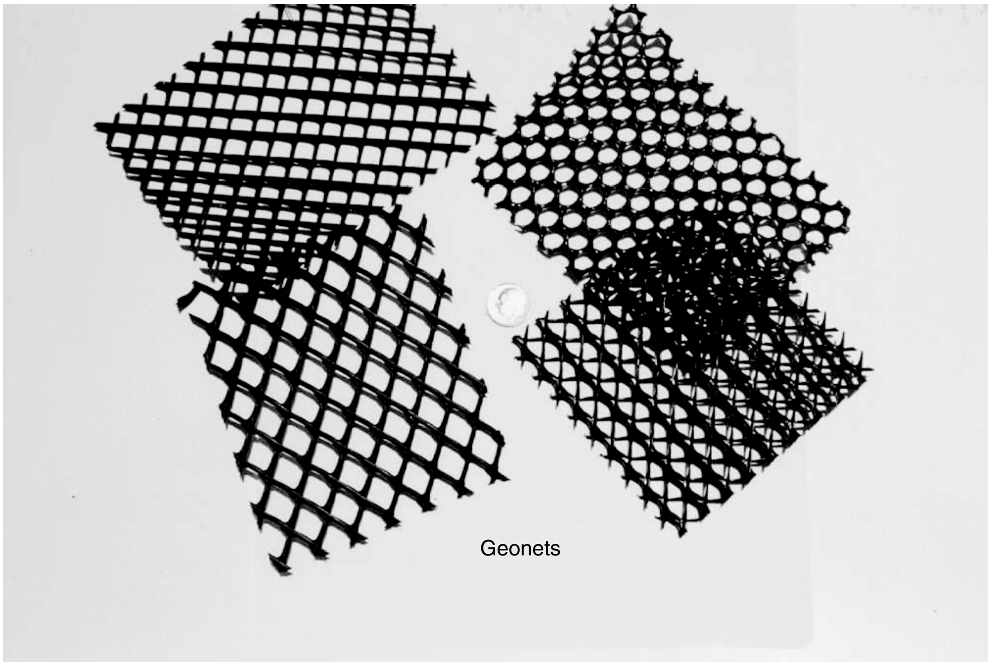

FIGURE 37.13 Typical geonets used as the core of geocomposite sheet drains.

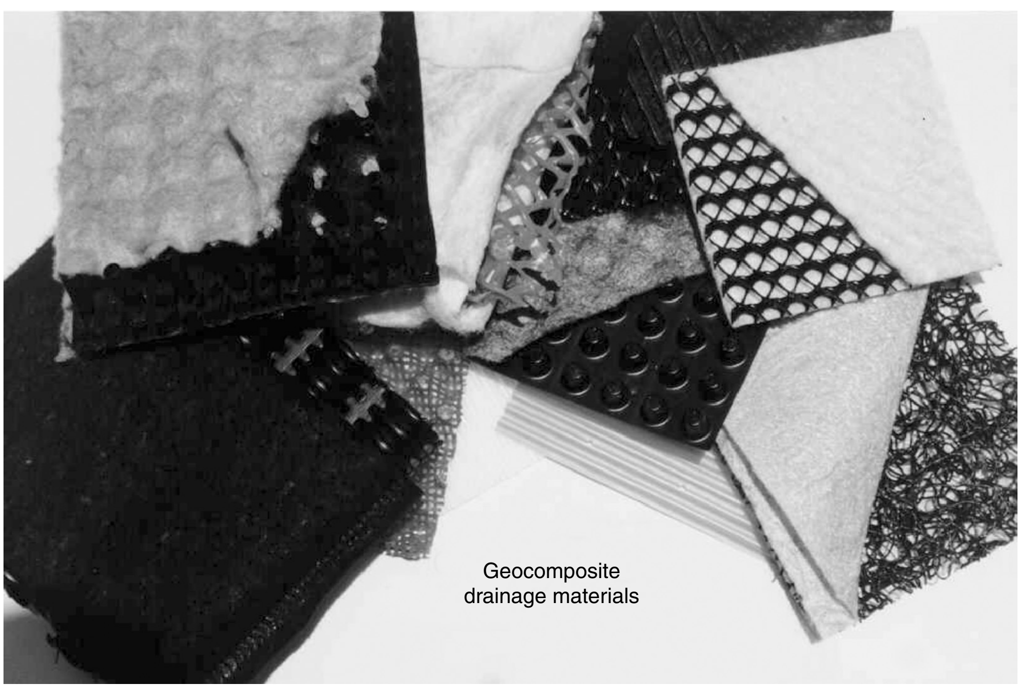

FIGURE 37.14 Typical geocomposite sheet drains.

TABLE 37.8 Standard Tests for Geocomposite Drainage Nets

Property	Test standard	Test name
Composite and core thickness	ASTM D 5199	Standard Test Method for Measuring Nominal Thickness of Geotextiles and Geomembranes
Core crush strength	ASTM D 1621	Standard Test Method for Compressive Properties of Rigid Cellular Plastics
Composite compression	ASTM D 6244	Test Method for Vertical Compression of Geocomposite Pavement Panel Drains
Composite compression	ASTM D 6364	Test Method for Determining Short-Term Compression Behavior of Geosynthetics
Composite transmissivity	ASTM D 4716	Standard Test Method for Determining the (In-plane) Flow Rate per Unit Width and Hydraulic Transmissivity of a Geosynthetic Using a Constant Head
Core carbon black	ASTM D 4218	Standard Test Method for Determination of Carbon Black Content in Polyethylene Compounds by the Muffle Furnace Technique
Geotextile filter	See Table 37.3	Grab Tensile Tear Strength CBR Puncture Strength AOS Permittivity

commonly performed to evaluate the properties of geocomposite sheet drains. It is also important to evaluate filtration requirements for the geotextile. Design and specification of composite drains is covered by Giroud et al. (2000), Koerner (2005), and Holtz et al. (1997, 1998).

37.3.6 Geocomposite Strip (Wick) Drains

Geocomposite strip drains, also called "wick drains," have been developed to replace the use of sand drains in applications involving the increase in consolidation rate of soft, saturated fine-grained soils. Geocomposite strip drains actually do not wick moisture, but simply provide a conduit for excess pore water pressure induced flow. They are placed vertically through high water content silts and clays to produce shortened drainage paths and thus increase the rate of consolidation. Other names commonly used for these products are "band shaped drains" and "prefabricated vertical drains."

Sand drains were originally introduced in the 1930s as a method for improvement of soft soil foundations. The method of rapid consolidation of saturated fine-grained soils using sand drains involves placement of vertical columns of sand (usually 200 to 450 mm in diameter) at spacings of 1.5 to 6.0 m centers throughout the subsurface to be dewatered. Due to the low installed product cost and speed of installation, the use of geocomposite strip drains dominates over the use of sand drains in projects involving dewatering of saturated fine-grained soils. Their lengths are site-specific and extend to the bottom of the soft layer, and, thus, lengths generally will vary along a project. Once installed, a surcharge load is placed on the ground surface to mobilize excess pore water pressures. This surcharge load is placed in incremental lifts, which induce pore water pressure in the underlying soil. The pore water pressure is then dissipated through the vertical drains. Water takes the shortest drainage path (i.e., horizontally radial) to the vertical drain, at which point it flows vertically as the drain has a much higher hydraulic conductivity than the fine-grained soil being consolidated. The rate at which surcharge fill is added is critical in this process.

Most commercially available geocomposite strip drains have adequate capacity to drain the water expelled during consolidation of the fine-grained soils. As their flow capacity is usually adequate, selection of the vertical drains is governed by the consolidation rate required in the project. Hansbo's equation (Hansbo, 1979) is generally used to estimate the time required to achieve a desired percentage of consolidation as a function of the horizontal coefficient of consolidation of the foundation soil, the equivalent diameter of the geocomposite strip drain, and the spacing of the drains. As with geocomposite sheet drains,

FIGURE 37.15 View of expanded geocell (photo courtesy of Presto Product Company).

the primary function of the geotextile covering is filtration. Determining the filtration requirements for the geotextile is an essential element of the design.

Installation of geocomposite strip drains is very rapid and uses lightweight construction equipment fitted with hollow leads (called a "lance" or mandrel) for insertion to the desired depth. The bottom of the lance should be covered by an expendable shoe that keeps soil out of the lance so as not to bind the strip drain within it. The allowable flow rate of geocomposite strip drains is determined by the ASTM D4716 test method. Typical values of ultimate flow rate at a hydraulic gradient of 1.0 under 207 kPa normal stress vary from 1.5 to 3.0 m^3/sec.-m. This value must then be reduced on the basis of site-specific partial factors of safety. Specifications for geocomposite strip drains are provided by Holtz et al. (1997).

37.3.7 Geocells

Geocells (or cellular confinement systems) are three-dimensional, expandable panels made from strips, typically 50 to 100 mm wide. When expanded during installation, the interconnected strips form the walls of a flexible, three-dimensional cellular structure into which specified infill materials are placed and compacted (Figure 37.15). This creates a system that holds the infill material in place and prevents mass movements by providing tensile reinforcement. Cellular confinement systems improve the structural and functional behavior of soil infill materials.

Geocells were developed in the late 1970s and early 1980s for support of military vehicles on weak subgrade soils. The original type of geocell consists of HDPE strips 200 mm wide and approximately 1.2 mm thick. They are ultrasonically welded along their 200 mm width at approximately 330 mm intervals and are shipped to the job site in a collapsed configuration. At the job site they are placed directly onto the subgrade surface and propped open in an accordion-like fashion with an external stretcher assembly. They are then filled generally with gravel or sand (although other infill materials such as concrete, can be used) and compacted using a vibratory hand-operated plate compactor. Geocell applications include protection and stabilization of steep slope surfaces, protective linings of channels and hydraulic structures, static and dynamic load support on weak subgrade soils, and multilayered earth-retaining and water-retaining gravity structures.

Geocells have proven very effective in providing a stable foundation over soft soils. The cellular confinement system improves the load-deformation performance of infill materials because cohesionless materials gain considerable shear strength and stiffness under confined conditions. Confining stresses are effectively induced in a geocell by means of the hoop strength developed by the HDPE cell walls. The overall increase in the load carrying performance of the system is provided through a combination of the cell wall strength, the passive resistance of the infill material in adjacent cells, and the frictional interaction between the infill soil and the cell walls. The cellular structure distributes concentrated loads to surrounding cells thus reducing the stress on the subgrade directly beneath the geocell.

Infill selection is primarily governed by the nature and intensity of anticipated working stresses, availability and cost of candidate materials, and aesthetic requirements for a fully vegetated appearance. Aggregates, vegetated topsoil, and concrete constitute typical geocell infill types. A complete cellular confinement system may also include geotextiles, geomembranes, geonets, geogrids, integral polymeric tendons, erosion-control blankets, and a variety of earth anchors.

37.3.8 Erosion Control Products

Erosion-control products represent one of the fastest growing application areas in the geosynthetics industry. Erosion-control products provide protection against sheet and gully erosion on soil slopes either until vegetation is established or for long-term applications. These products can be classified as temporary degradable erosion control blankets, long-term nondegradable erosion control mats, and permanent hard armored systems.

Temporary degradable erosion control blankets are used to enhance the establishment of vegetation. These products are used where vegetation alone would provide sufficient site protection once established after the erosion control product has degraded. Some of these products are completely biodegradable (e.g., straw, hay, jute, and hydraulic mulches), while others are only partially biodegradable (e.g., erosion control meshes and nets).

Long-term nondegradable erosion control mats provide permanent reinforcement of vegetation root structure. They are used in critical erosion-control applications where immediate high-performance erosion protection, followed by the permanent reinforcement of established vegetation is required. These soft armor related products provide erosion control, aid in vegetative growth, and eventually become entangled with the vegetation to provide reinforcement to the root system.

Finally, the permanent hard armored systems include riprap on geotextile filters, modular concrete block over geotextile filter systems, gabions over geotextile filters, geocell products with gravel or concrete infill, vegetated concrete block systems, and fabric-formed revetments.

Figure 37.16 shows an erosion control mat installed to help vegetation establishment on a steep reinforced soil slope. Installation of flexible erosion control products is straightforward. The products are usually placed on a prepared soil surface (e.g., facing of the reinforced embankment in Figure 37.16) by stapling or pinning them to the soil surface. Intimate contact between the blanket or mat and the soil is very important as water flow beneath the material has usually been the cause of poor functioning.

37.3.9 HDPE Vertical Barrier Systems

The use of geomembranes (Section 37.3.2) as horizontal barrier layers has been extended for the case of seepage control in remediation projects, in which vertically deployed geomembranes are used in vertical cutoff trenches. The construction process involves excavation of a trench and placement of a seamed geomembrane in the open trench. This procedure is usually not possible for deep trenches due to the potential collapse of the sidewalls, so the use of slurry to stabilize the trench becomes necessary. The mixture of water and bentonite clay balances the pressures exerted by the *in situ* soils. The geomembrane

FIGURE 37.16 Erosion control mat placed to help establish the vegetation on the face of a 1H:1V reinforced soil slope.

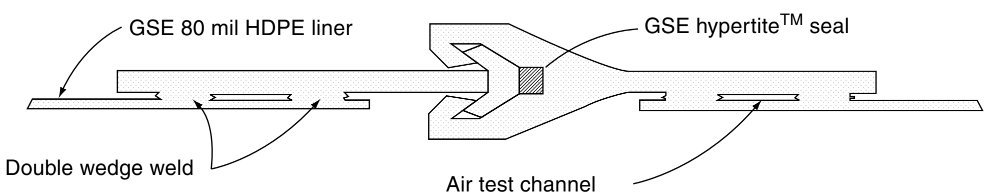

FIGURE 37.17 Interlocking system for HDPE vertical barriers (figure courtesy of GSE Lining Technology, Inc.).

is placed in the slurry after trench excavation to the intended depth. Once the geomembrane is in place the backfill can be introduced, displacing the slurry and forcing the geomembrane to the side of the trench.

As installation of vertically deployed conventional geomembranes is difficult, other systems have become available. These systems involve the use of thick HDPE or nonplasticized PVC geomembranes in the form of tongue-and-groove sheeting. Sealing of the interlocks is often achieved by using chloroprene-based, hydrophilic seals. Figure 37.17 shows one type of interlocking system with a hydrophilic seal. The seal is an extruded profile, typically 8 mm in diameter, which can expand up to eight times its original volume when exposed to water. These interlocking HDPE vertical barrier systems are being increasingly used as an alternative to soil-bentonite slurry walls, especially in projects involving areas of limited access, high disposal costs, depths where performance of a slurry wall is questionable and high concentrations of saline and chemicals.

An additional advantage of the HDPE vertical barrier system is that it can work both as containment and a collection system (e.g., a composite sheet drain) and can be constructed in one trench. A recently developed method utilizes a biopolymer, or biodegradable, slurry. These slurries allow the HDPE panels and collection system (e.g., geocomposite sheet drains) to be installed in the same trench. Unlike bentonite, these slurries will either biodegrade or can be reversed to allow the collection system to drain clear and free of fines.

Another method of achieving construction of a containment and collection system in the same trench has been developed which utilizes a trenchless, vibratory method for installation of the HDPE panels and geocomposite sheet drains. First, a collection trench is constructed to the required depth. This is followed with the installation of the geomembrane panel using modified pile-driving techniques. Panel widths ranging typically between 0.91 to 1.83 m are driven to depths up to 12 m. This construction method is most often reserved for sites on which excavation and disposal costs are high, access is limited, or the barrier is too close to a body of water. A case history in which this installation method was used for placement of an HDPE vertical barrier system is described in Section 37.5.1 .

A recent development in the installation of these systems is the use of a "one-pass" deep trencher. Installation of HDPE vertical barrier systems using this technology has proven to be fast and safe. A special trencher equipment can install a vertical geomembrane wall with a collection system consisting of a HDPE pipe and gravel fill in one trench, in one pass. Figure 37.18 shows the placement of an HDPE panel using this one-pass deep trencher.

FIGURE 37.18 One pass trencher for installation of an HDPE vertical barrier system. (Photo courtesy of Groundwater Control, Inc.)

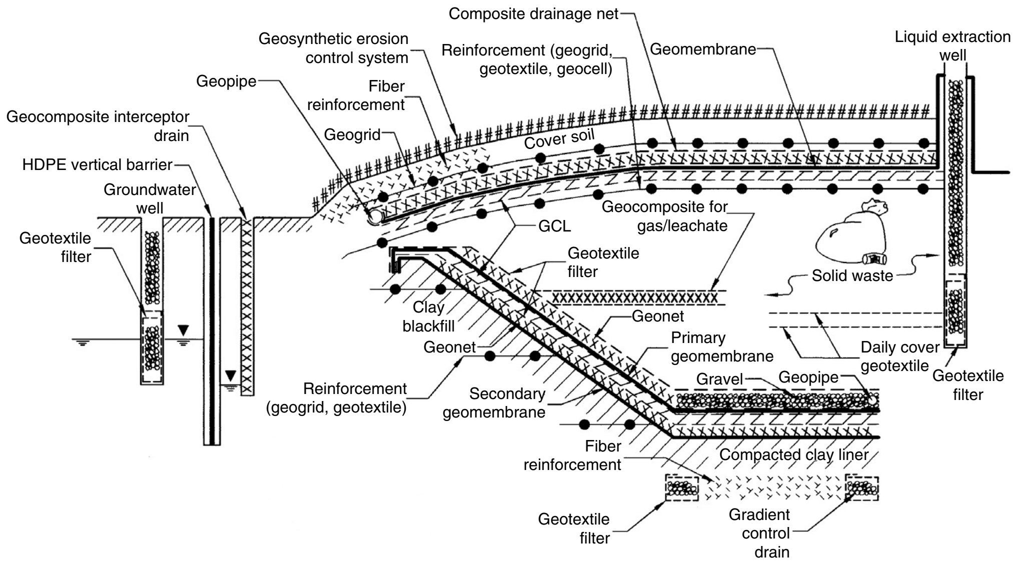

FIGURE 37.19 Multiple use of geosynthetics in landfill design.

37.4 Geosynthetic Applications in Landfill Design

The multiple uses of geosynthetics in the design of modern municipal solid waste landfills is a good illustration of an application in which different geosynthetics are used to perform all the functions discussed in Section 37.2. Virtually all the different types of geosynthetics discussed in Section 37.3 have been used in the design of both base and cover liner systems of landfill facilities. The extensive use of geosynthetics in modern landfills has been triggered by the economical and technical advantages that geosynthetics offer in relation to traditional liner systems. A geomembrane infiltration barrier and geocomposite sheet drain collection layers of a few millimeters in thickness can provide equivalent performance as a soil infiltration barrier with a gravel collection layer and graded granular filter layer of up to several meters in thickness.

Landfill base liners are placed below the waste to minimize the release of liquids from the waste (i.e., leachate). Leachate is the main source of contamination of the soil underlying the landfill and, most importantly, the groundwater. Landfill cover liners are placed above the final waste configuration to prevent water, usually from rain or snow, from percolating into the waste and producing leachate. Waste containment systems employ geosynthetics to varying degrees. Figure 37.19 illustrates the extensive multiple uses of geosynthetics in both the cover and the base liner systems of a modern landfill facility.

The base liner system illustrated in Figure 37.19 is a double composite liner system. Double composite liner systems are used in some instances for containment of municipal solid waste and are frequently used for landfills designed to contain hazardous waste. The base liner system shown in this figure includes a geomembrane/GCL composite as the primary liner system and a geomembrane/compacted clay liner composite as the secondary system. The leak detection system, located between the primary and secondary liners, is a geotextile/geonet composite. The leachate collection system overlying the primary liner on the bottom of the liner system consists of gravel with a network of perforated pipes. A geotextile protection layer beneath the gravel provides a cushion to protect the primary geomembrane from puncture by stones in the overlying gravel. The leachate collection system overlying the primary liner on the side slopes of the liner system is a geocomposite sheet drain (geotextile/geonet composite) merging into the gravel on the base. A geotextile filter covers the entire footprint of the landfill and prevents clogging of the leachate collection and removal system. The groundwater level may be controlled at the bottom of the landfill by gradient control drains built using geotextile filters. Different types of geosynthetics (e.g., geogrids, geotextiles, fibers) can be selected for stabilization of the foundation soils.

The cover system of the landfill illustrated in Figure 37.19 contains a composite geomembrane/GCL barrier layer. The drainage layer overlying the geomembrane is a geocomposite sheet drain (composite geotextile/geonet). In addition, the soil cover system may include geogrid, geotextile, or geocell reinforcements below the infiltration barrier system. This layer of reinforcements may be used to minimize the strains that could be induced in the barrier layers by differential settlements of the refuse or by a future vertical expansion of the landfill. In addition, the cover system could include a geogrid or geotextile reinforcement above the infiltration barrier to provide stability to the vegetative cover soil. Fiber reinforcement may also be used for stabilization of the steep portion of the vegetative cover soil. A geocomposite erosion control system above the vegetative cover soil is indicated in the figure and provides protection against sheet and gully erosion.

Figure 37.19 also illustrates the use of geosynthetics within the waste mass, which are used to facilitate waste placement during landfilling. Specifically, the figure illustrates the use of geotextiles as daily cover layers and of geocomposites within the waste mass for collection of gas and leachate. Geotextile filters are also extensively used for leachate collection and detection blanket drains and around the gravel in leachate collection trenches at the base of the landfill. Geosynthetics can also be used as part of the groundwater and leachate collection well system. The use of geotextiles as filters in groundwater and leachate extraction wells is also illustrated in the figure. Finally, the figure shows the use of a HDPE vertical barrier system and a geocomposite interceptor drain along the perimeter of the landfill facility. Although not all of the components shown in Figure 37.19 would normally be needed at any one landfill facility, the figure illustrates the many geosynthetic applications that can be considered in landfill design.

Bouazza et al. (2002) provide an update on the use of geosynthetics in the design of waste containment facilities. A case history involving the design of a liner system with multiple uses of geosynthetics is described in Section 37.5.2.

37.5 Case Histories

37.5.1 Case History of Vertical Barrier System

Although the use of geosynthetics in many geotechnical and environmental projects is related to groundwater applications (e.g., landfill liners, which prevent groundwater contamination), a geosynthetic application directly related to groundwater remediation and control is the use of HDPE panels as vertical barrier systems. A case history is presented herein to illustrate the use of HDPE panels as part of a remediation plan for a site contaminated with coal tar (Burson et al., 1997).

The site was a defunct manufactured gas plant located in York, Pennsylvania. The site is surrounded by commercial and residential areas and a creek (Codorus Creek) borders the site for a distance of approximately 305 m. During years of operation and the subsequent closure of the manufactured gas plant, some process residuals migrated to the subsurface soils and groundwater. Over time, the presence of a coal tar-like material in the form of a dense non-aqueous phase liquid (DNAPL), was observed seeping from the bank of the Codorus Creek. DNAPL was also noted in some on-site monitoring wells.

Several remediation scenarios were evaluated with the purpose of intercepting the tar-like material migrating through the soil and into groundwater, encountered approximately 5.0 m below ground surface. A system consisting of a combination of soil improvement by jet grouting, a vertical barrier using HDPE panels, and a network of recovery wells was finally selected.

The use of vertical HDPE panels and trenchless technology allowed placement of the barrier as close as 3 m from the bank of the Codorus Creek, which was difficult to achieve with conventional slurry wall technology. The HDPE barrier system selected for this project was a 2 mm thick geomembrane, which allowed for the vibratory, trenchless installation. Sealing of the interlocks was achieved with a chloroprene-based, hydrophilic seal (see Figure 37.17). HDPE panels were keyed into the soil improved by jet grouting,

FIGURE 37.20 Installation of HDPE barrier wall utilizing conventional pile driving equipment. (Photo courtesy of Groundwater Control Inc.)

as discussed below. The panels were installed using conventional vibratory pile driving equipment, without a trench, thus reducing the amount of contaminated spoils to be disposed (Figure 37.20).

To complete closure of the contaminated material, jet grouting was used to provide a seal to control DNAPL migration between the bottom of the HDPE panels and the irregular bedrock contact. Jet grouting consists of high pressure injection of cement and bentonite slurry, horizontally into the soil strata to improve its mechanical and hydraulic properties. The containment wall was approximately 290 m in length. The soil along the alignment of the barrier system consisted of granular fills, with large amounts of cinder material. Also mixed into the fill were varying amounts of rubble and debris. These highly permeable soils were underlain by the competent bedrock. Holes were pre-drilled down to bedrock, and the jet grouting improvement was done by injecting the grout horizontally from the competent rock up to an elevation approximately 6 m below the ground surface.

A groundwater recovery system was implemented once the barrier was completed. Since its installation in the fall of 1995, the HDPE panel jet grout barrier system has performed as intended.

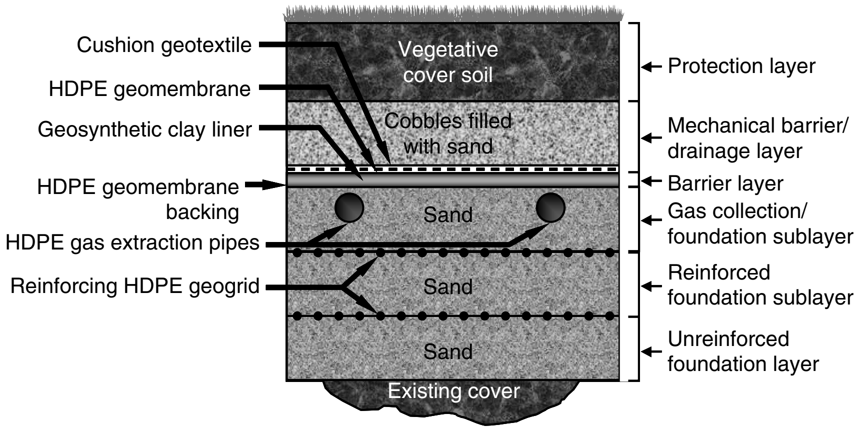

FIGURE 37.21 Cover system reinforced using geogrids.

37.5.2 Case History of Multiple Use of Geosynthetics in Landfill Cover Design

The cover system at the McColl Superfund Site, Fullerton, California is a good example of a site where multiple systems of soil reinforcement were used for stabilization of the final cover system. One of these uses involves placement of geogrids along the cover system. The project also included the construction of conventional reinforced structures (Collins et al., 1998; Hendricker et al., 1998).

The site has 12 pits containing petroleum sludge and oil-based drilling muds. The sludge was generated by the production of high-octane aviation fuel and was placed into the pits between 1942 and 1946. Between 1952 and 1964, the site was used for disposal of oil-based drilling muds. These wastes and their reaction products and byproducts were found as liquid, gas, and solid phases within the pits. At the time of deposition, essentially all of the waste materials were mobile. Over time, much of the waste had hardened. The drilling mud is a thixotropic semi-solid sludge, which can behave as a very viscous fluid.

Key considerations for the selection of the final remedy were to: (1) provide a cover system that includes a barrier layer and a gas collection and treatment system over the pits to minimize infiltration of water and release of hazardous or malodorous gas emissions; (2) provide a subsurface vertical barrier around the pits to minimize outward lateral migration of mobile waste or waste byproducts and inward lateral migration of subsurface liquid; and (3) provide slope stability improvements for unstable slopes at the site.

The geogrid reinforcement for the cover system over the more stable pits was constructed with two layers of uniaxial reinforcement placed orthogonally to one another. Connections at the end of each geogrid roll were provided by Bodkin joints. Adjacent geogrid panels did not have any permanent mechanical connections. This proved to be somewhat problematic, as additional care was required during placement of the overlying gas collection sand to minimize geogrid separation. Details of the cover system involving geogrid reinforcement are shown in Figure 37.21.

A geocell reinforcement layer was constructed over the pits containing high percentages of drilling mud. While the construction of this reinforcement layer proceeded at a slower pace than the geogrid reinforcement, it did provide an immediate platform to support the load. As the bearing capacity of the underlying drilling mud was quite low, the geocell provided load distribution, increasing the overall bearing capacity of the cover system. Details of the cover system involving geogrid reinforcement are shown in Figure 37.22.

In addition to reinforced covers, three conventional reinforced soil structures were constructed at the site. One of the structures was necessary to provide a working pad for construction of the subsurface vertical barrier. This reinforced earth structure had to support the excavator with a gross operating weight of 1100 kN that was used to dig the soil-bentonite cutoff wall. Another reinforced earth structure at the site

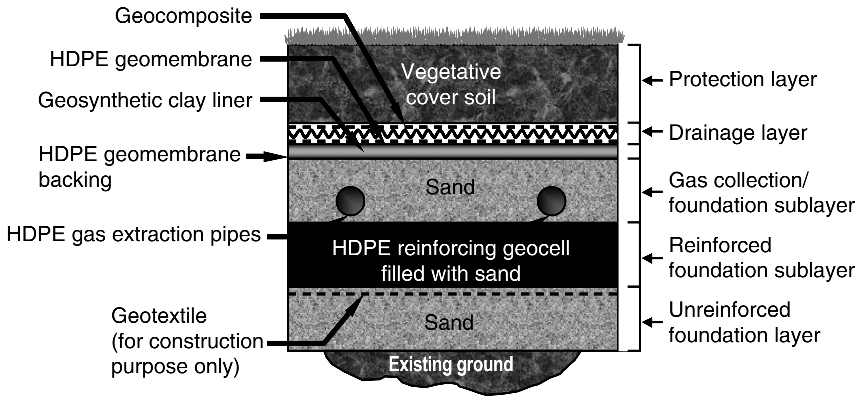

FIGURE 37.22 Cover system reinforced using geocells.

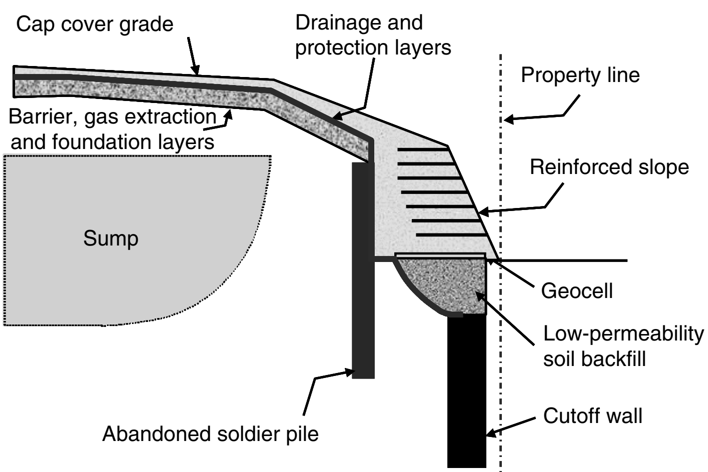

FIGURE 37.23 Buttressing reinforced slope at McColl Superfund site.

had to span a portion of the completed cutoff wall. Due to concerns that the stress of the reinforced earth structure on the underlying soil-bentonite cutoff wall would lead to excessive deformation of the wall due to consolidation of the cutoff wall backfill, a flexible wall fascia was selected. As shown in Figure 37.23, a soldier pile wall was constructed to provide stability of the system during construction. The use of geosynthetic alternatives in this project was more suitable and cost effective than their conventional counterparts.

Glossary

Alloys, polymeric a blend of two or more polymers (e.g., a rubber and plastic) to improve a given property (e.g., impact strength).

Apparent opening size (AOS), O_{95} for geotextile, a property which indicates the diameter of the approximate largest particle that would effectively pass through the geotextile. At least 95% of the openings apparently have that diameter or are smaller as measured by the dry sieve test.

Chemical stability stability of a geosynthetic; ability to resist degradation from chemicals, such as acids, bases, solvents, oils and oxidation agents; and chemical reactions, including those catalyzed by light.

Chlorosulfonated polyethylene (CSPE) family of polymers that is produced by polyethylene reacting with chlorine and sulfur dioxide. Present CSPEs contain 25 to 43% chlorine and 1.0 to 1.4% sulfur.

Clogging movement by mechanical action or hydraulic flow of soil particles into the voids of fabric and retention therein, thereby reducing the hydraulic conductivity of the geotextile.

Cross-machine direction the axis within the plane of a fabric perpendicular to the predominant axis of the direction of production.

Cross-plane The direction of a geosynthetic that is perpendicular to the plane of its manufactured direction. Referred to in hydraulic situations.

Fiber basic element of fabrics and other textile structures, characterized by having a length at least 100 times its diameter or width that can be spun into a yarn or otherwise made into a fabric.

Filament yarn the yarn made from continuous filament fibers.

Filtration in geotextiles; the process of retaining soil in place while allowing water to pass from soil. In chemistry, removal of particles from a fluid stream.

Geocell a three-dimensional structure filled with soil, thereby forming a mattress for increased stability when used with loose or compressible subsoils.

Geocomposite a manufactured material using geotextiles, geogrids, and geomembranes in laminated or composite form. May or may not include natural materials.

Geogrid open grid structure of orthogonal filaments and strands of polymeric material used primarily for tensile reinforcement.

Geomembrane very low hydraulic conductivity synthetic membrane liners or barriers used with any geotechnical engineering related material so as to control fluid migration in a man-made project, structure, or system.

Geonet a geosynthetic consisting of integrally connected parallel sets of ribs overlying similar sets at various angles for planar drainage of liquids or gases.

Geopipe any plastic pipe used with foundation, soil, rock, earth, or any other subsurface related material as an integral part of a human-made project, structure, or system.

Geosynthetic a planar product manufactured from polymeric material used with soil, rock, earth, or other geotechnical engineering related material as an integral part of a constructed project, structure, or system.

Geosynthetic clay liner (GCL) factory-manufactured hydraulic barriers consisting of a layer of bentonite clay or other very low permeability material supported by geotextiles and geomembranes, and mechanically held together by needling, stitching, or chemical adhesives.

Geotextile any permeable textile used with foundation, soil, rock, earth, or any other geotechnical engineering-related material as an integral part of a constructed project, structure, or system.

Grab test in fabric testing, a tension test in which only a part of the width of the specimen is gripped in the clamps.

Gradient ratio the ratio of the average hydraulic gradient across the fabric and the 25 mm of soil immediately next to the fabric to the average hydraulic gradient across the 50 mm of soil between 25 and 75 mm above the fabric, as measured in a constant head permeability test.

Heat bonded thermally bonded by melting the fibers to form weld points.

Hot wedge common method of heat seaming thermoplastic geomembranes by a fusing process wherein heat is delivered by a hot wedge passing between the opposing surfaces to be bonded.

Hydraulic transmissivity for a geotextile or related product, the volumetric flow rate of water per unit width of specimen per unit gradient in a direction parallel to the plane of the specimen.

Index test a test procedure that may contain a known bias but which may be used to establish an order for a set of specimens with respect to the property of interest.

In-plane the direction of a geosynthetic that is parallel to its longitudinal, manufactured, or machine direction. Referred to in hydraulic situations.

Leachate liquid that has percolated through or drained from solid waste or other human-emplaced materials and contains soluble, partially soluble, or miscible components removed from such waste.

Liner a layer of emplaced materials beneath a surface impoundment or landfill that serves to restrict the escape of waste or its constituents from the impoundment or landfill.

Machine direction the direction in the plane of the fabric parallel to the direction of manufacture.

Mass per unit area the proper term to represent and compare the amount of material per unit area (units are or g/m^2) of a geosynthetic.

Monofilament a single filament of a fiber (normally synthetic).

Mullen burst hydraulic bursting strength of textiles.

Multifilament a yarn consisting of many continuous filaments or strands.

Needlepunched in geotextiles, mechanical bonding of staple or filament fibers with barbed needles to form a compact fabric.

Nonwoven fabric a textile structure produced by bonding or interlocking of fibers, or both, accomplished by mechanical, thermal, or chemical means.

Permittivity of geotextiles and related products, the volumetric flow rate of water per unit cross sectional area per unit head under laminar flow conditions, in the normal direction through a geotextile.

Plasticizer a plasticizer is a material, frequently solvent-like, incorporated in a plastic or a rubber to increase its ease of workability, its flexibility, or distensibility.

Polyester fiber generic name for a manufactured fiber in which the fiber-forming substance is any long-chain synthetic polymer composed of an ester of a dihydric alcohol and terepthalic acid.

Polyethylene a polyolefin formed by bulk polymerization (for low density) or solution polymerization (for high density) where the ethylene monomer is placed in a reactor under high pressure and temperature.

Polymer a macromolecular material formed by the chemical combination of monomers having either the same or different chemical composition. Plastics, rubbers, and textile fibers are all high-molecular-weight polymers.

Polyolefin a family of polymeric materials that includes polypropylene and polyethylene, the former being very common in geotextiles and the latter in geomembranes.

Polyvinyl chloride (PVC) a synthetic thermoplastic polymer prepared from vinyl chloride.

Quality assurance (QA) a planned system of activities whose purpose is to provide a continuing evaluation of the quality control program, initiating corrective action where necessary. It is applicable to both the manufactured product and its field installation.

Quality control (QC) actions that provide a means of controlling and measuring the characteristics of (both) the manufactured and the field installed product.

Separation the function of geosynthetics as a partition between two adjacent materials (usually dissimilar) to prevent mixing of the two materials.

Specification a precise statement of a set of requirements to be satisfied by a material, product, system, or service that indicates the procedures for determining whether each of the requirements is satisfied.

Spun-bonded fabrics fabric formed by continuous filaments that have been spun (extruded), drawn, laid into a web and bonded (chemical, mechanical, or thermal bonding) together in one continuous process.

Staple fibers fibers of short lengths; frequently used to make needlepunched nonwoven fabrics.

Subgrade intrusion localized aggregate penetration of a soft cohesive subgrade and resulting displacement of the subgrade into the cohesionless material.

Subgrade pumping the displacement of cohesive or low-cohesion fines from a saturated subgrade into overlying aggregate as the result of hydraulic forces created by transmittal of wheel-load stresses to the subgrade.

Survivability the ability of a geosynthetic to be placed and to perform its intended function without undergoing degradation.

Tensile strength the maximum resistance to deformation developed for a specific material when subjected to tension by an external force.

Trapezoid Tear Test test method used to measure the tearing strength of geotextiles.

Transmissivity for a geosynthetic, the volumetric flow rate per unit thickness under laminar flow conditions, in the in-plane direction of the fabric or geocomposite.

Ultraviolet degradation the breakdown of polymeric structure when exposed to natural light.

Woven geotextilea planar geotextile structure produced by interlacing two or more sets of elements such as yarns, fibers, rovings of filaments where the elements pass each other usually at right angles and one set of elements are parallel to the fabric axis.

Wide-width strip tensile test a uniaxial tensile test in which the entire width of a 200 mm wide specimen is gripped in the clamps and the gauge length is 100 mm.

Yarn a generic term for continuous strand strands (1 or more) of textile filaments, monofilaments, or slit form suitable for knitting, weaving, or otherwise intertwining or bonding to form a textile fabric.

Sources for these and other definitions of terms can be found in ASTM (1997) and Koerner (2005).

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Further Information

Koerner (2005) provides an excellent, well-illustrated overview of the different types of geosynthetics and their applications.

Holtz, Christopher and Berg (1997, 1998) provide well-documented practical design and construction information on the different uses of geosynthetic products.

Giroud et al. (1993, 1994) provide a two-volume comprehensive database on technical literature relative to geosynthetics, including technical papers from conferences, technical papers from journals, books, theses, and research reports.

Technical advances on geosynthetics are also published in the two official journals of the IGS: Geosynthetics International, and Geotextiles and Geomembranes. Similarly, the Geotechnical Fabrics Report (GFR), published by the Industrial Fabrics Association International (IFAI) provides updated information, including the annual Specifier's Guide, which offers a summary of the properties of products available in the geosynthetics market.

The ASTM Standards on Geosynthetics, sponsored by ASTM Committee D-35 on Geosynthetics (ASTM, 1995), provides information on the standard test procedures for the different types of geosynthetics.

The proceedings of the International Conferences on Geosynthetics, organized by the International Geosynthetic Society (IGS), offer a relevant source of information on the different topics related to geosynthetics. These international conferences are organized every four years. Equally relevant are the proceedings of conferences organized by the regional chapters of IGS. Finally, the proceedings of the series of conferences organized by the Geosynthetics Research Institute (GRI) provide information on specific topics relevant to geosynthetic design.

Geosynthetic manufacturers' literature is also a valuable source of information, which provides product-specific properties, suggested design methods, and recommended factors of safety.