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27

Geosynthetics

Jorge G. Zornberg
University of Colorado at Boulder

Barry R. Christopher
Independent Consultant

27.1 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 and environmental applications related to groundwater quality and control. This is the case, for example, of base and cover liner systems for modern landfills, which are designed making extensive use of geosynthetics. The main purpose of geosynthetic liner systems is to minimize potential groundwater contamination. Moreover, 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 are used instead of traditional soil-bentonite cutoff walls in projects involving groundwater remediation and control.

The geosynthetics market is strong and rapidly increasing because of the continued use of geosynthetics in well-established applications and, particularly, because of the increasing number of new applications which 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. While the total amount of geosynthetics produced in North America was slightly more than 83 million m^2 in 1980, the production of geosynthetics exceeded 500 million m^2 in 1995. Table 27.1 shows the estimated North American shipments of geosynthetics for 1995 and predictions until 2001. Collectively, 150 manufacturers of geosynthetic products shipped 525 million m^2 of material in 1995 and grew at an annual rate of 7% (Industrial Fabrics Association International, 1996). In the 2001 forecast period, manufacturers are expected to ship approximately 734 million m^2 of materials.

TABLE 27.1 North American Shipments of Geosynthetic Materials, 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	22.9	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

From Industrial Fabrics Association International. 1996. *North American Market for Geosynthetics — 1996.*

Geosynthetics applications are very diverse. In order to fulfill different functions in the design of geotechnical-, environmental-, and groundwater-related systems, the geosynthetic industry has developed a number of products. In addition to the already mentioned examples regarding use of geomembranes in landfill liner systems and the use of 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 a few more.

Geosynthetics have numerous material properties. Many of the reported properties are important in the manufacture and quality control of geosynthetics; however, many others are also important in design. The material properties related to the manufacture and quality control of geosynthetics are generally referred to as index properties and those related to the design as design or performance properties. Considering their different properties, the several geosynthetic products can perform different functions and, consequently, they should be designed to satisfy minimum criteria to adequately perform these functions. The different functions performed by geosynthetics are discussed in Section 27.2. The geosynthetic functions are as follows:

- Separation
- Reinforcement
- Filtration
- Drainage
- Infiltration barrier
- Protection (or stress relief)

Geosynthetics are manufactured in a factory-controlled environment. They are packaged in sheets, placed in a roll or carton, and finally transported to the site. At the project site the geosynthetic sheets are unrolled on the prepared subgrade surface, overlapped to each other to form a continuous geosynthetic blanket, and often physically joined to each other. The individual types of products within the geosynthetics family are discussed in Section 27.3. The geosynthetic types are as follows:

- Geotextiles
- Geomembranes
- Geogrids
- Geosynthetic clay liners (GCLs)
- Geocomposite sheet drains
- Geocomposite strip (wick) drains
- Geocells
- Erosion control products
- HDPE vertical barrier systems

Note in the list above that different types of geocomposite drains are treated separately, and that HDPE vertical barriers are not lumped together with the rest of the geomembrane products. These geosynthetics are described separately in this chapter because of their particular relevance in groundwater-related applications.

Geotechnical, environmental, and groundwater systems frequently incorporate several types of geosynthetics, which are designed to perform more than one function in the system. The bottom and cover liners 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 fulfill the functions of infiltration barrier, filtration, separation, drainage, protection, and reinforcement. The multiple use of geosynthetics in the design of modern landfills is described in Section 27.4. Finally, a case history illustrating the use of HDPE panels as a vertical barrier in a groundwater control project is presented in Section 27.5. A glossary of relevant terms and a list of sources are included for further information.

27.2 Geosynthetic Functions

27.2.1 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 geosynthetic design methods are by experience, by specification, or by function (Koerner, 1994).

Design-by-experience is generally based on the use of the manufacturer's literature and of the designer's experience and familiarity with geosynthetic products. Design-by-specification is practiced, for example, by government agencies (e.g., state departments of transportation) for routine applications. It often consists in selecting geosynthetic products for common application areas, taking as a basis minimum- or maximum-specified property values.

Design-by-function can be used in addition to the aforementioned methods and is required for those 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, 1994):

1. Evaluate the criticality and severity 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
5. Calculate the factor of safety (*FS*) ratio as follows:

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

6. Determine if the resulting factor of safety is significantly high 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 is 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 of geosynthetics is either separation, reinforcement, filtration, drainage, infiltration barrier, or protection. However, a certain geosynthetic product can perform different

TABLE 27.2 Function of Different Geosynthetic Products

	Geo-textile	Geo-membrane	Geo-grid	GCL	Geo-composite Sheet Drain	Geo-composite Strip (Wick) Drain	Geocell	Erosion Control Product	HDPE Vertical Barrier
Separation	X						X	X	
Reinforcement	X		X				X		
Filtration	X								
Drainage	X				X	X			
Infiltration barrier	X[1]	X		X					X
Protection	X			X					

[1] Asphalt-saturated geotextiles

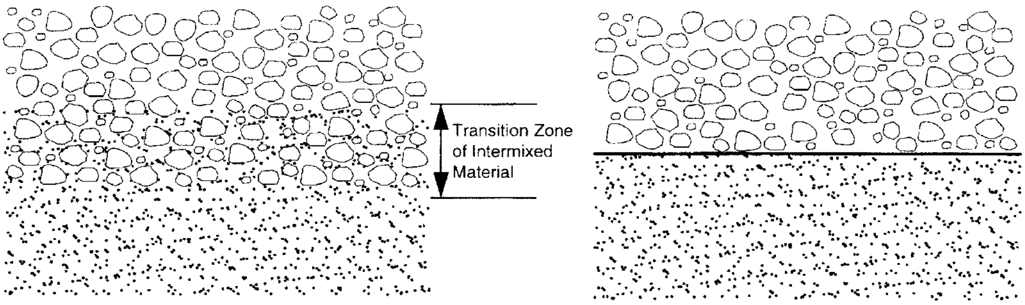
functions and, similarly, the same function can often be performed by different types of geosynthetics. The specific function(s) of the different geosynthetic(s) are presented in Table 27.2. Each of these functions is described in Sections 27.2.2 to 27.2.7.

27.2.2 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 courses with the underlying soft subgrade soils (Figure 27.1A). Contamination occurs due to: (1) penetration of the aggregate into the weak subgrade due to localized bearing capacity failure under stresses induced by wheel loads, and (2) inclusion of fine-grained soils into the aggregate because of pumping or subgrade weakening due to excess pore water pressures. Subgrade contamination results in inadequate structural support, which 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 27.1B).

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 geosynthetics generally include separation as a secondary function.

Geosynthetics used as erosion control systems can also be considered as performing a separation function. In this case, the geosynthetic separates the ground surface from the prevailing atmospheric



(A) Without Geotextile

(B) With Geotextile

FIGURE 27.1 Separation function of a geotextile placed between road aggregate and soft subgrade.

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. General references on the design of geosynthetics for separation applications can be found in Christopher and Holtz (1985) and in Koerner (1994).

27.2.3 Reinforcement Function

Geosynthetic inclusions within a soil mass can provide a reinforcement function by developing tensile forces which contribute to the stability of the geosynthetic–soil composite (a reinforced soil structure). Design and construction of stable slopes and retaining structures within space constraints are aspects of major economical significance in geotechnical engineering projects. For example, when geometry requirements dictate changes of elevation in a highway project, the engineer faces a variety of distinct alternatives for designing the required earth structures. Traditional solutions have been either a concrete retaining wall or a conventional, relatively flat, unreinforced slope (Figure 27.2). 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.

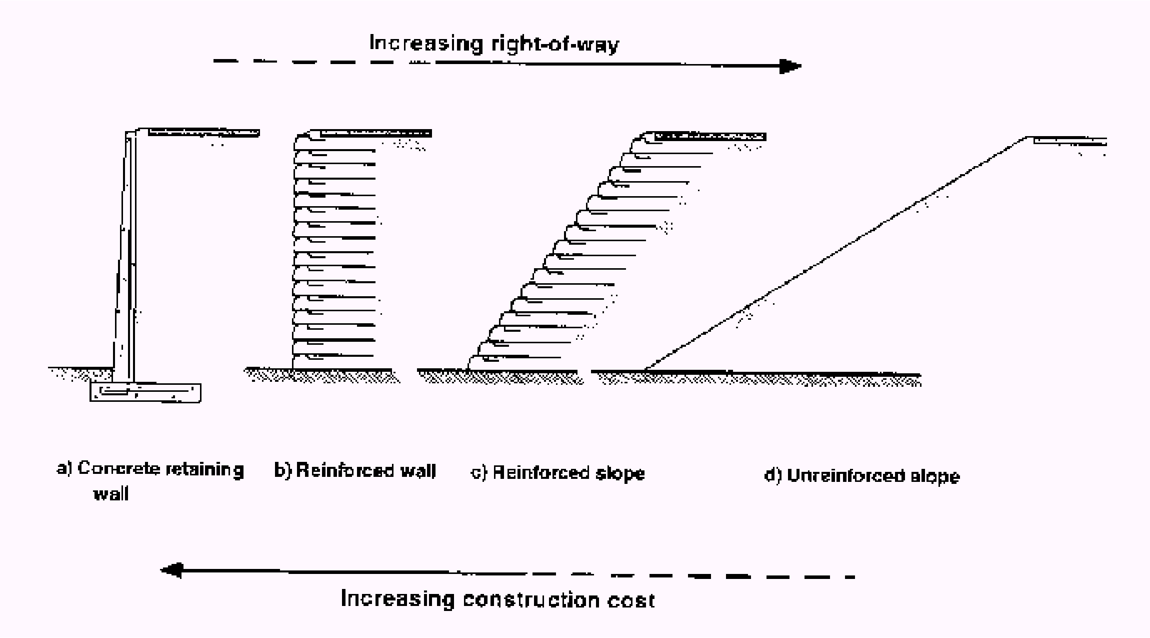


FIGURE 27.2 Reinforcement function of geosynthetics used to optimize the design of earth retaining structures.

Geosynthetics are particularly suitable for soil reinforcement. Geosynthetic products typically used as reinforcement elements are nonwoven geotextiles, woven geotextiles, geogrids, and geocells. Reinforced soil vertical walls generally provide vertical grade separations at a lower cost than traditional concrete walls. Reinforced wall systems involve the use of shotcrete facing protection or of facing elements such as precast or cast-in-place concrete panels. Alternatively, steepened reinforced slopes may eliminate the use of facing elements, thus saving material costs and construction time in relation to vertical reinforced walls. As indicated in Figure 27.2, a reinforced soil system generally provides an optimized alternative for the design of earth-retaining structures.

The effect of geosynthetic reinforcements on the stability of sand slopes is illustrated in Figure 27.3, which shows a reduced scale geotextile-reinforced slope model built using dry sand as backfill material.

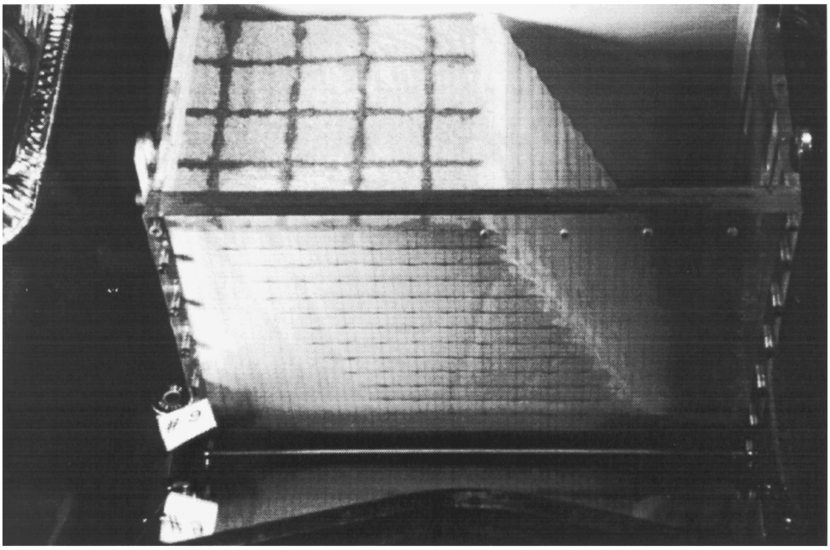


FIGURE 27.3 Model of a sand slope reinforced with geosynthetics.

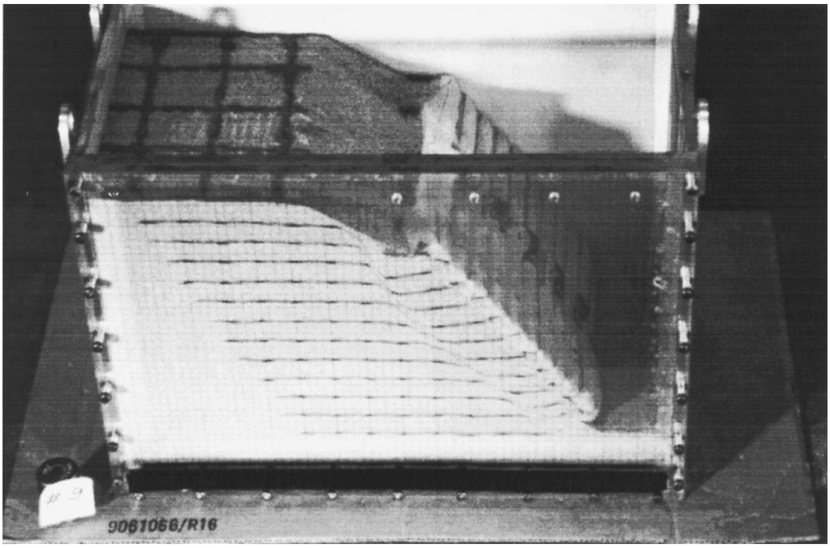


FIGURE 27.4 Reinforced slope model brought to failure by increasing the unit weight of the backfill.

The maximum slope inclination of an 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. 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 after the unit weight of the backfill was increased 67 times by placing the model in a geotechnical centrifuge (Zornberg et al., 1997). Figure 27.4 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 quarter of century or so (Vidal, 1969) that analytical and experimental studies have led to 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. Moreover, its acceptance has also been triggered by a number of technical factors, that include aesthetics, reliability, simple construction techniques, good seismic performance, and the ability to tolerate large deformations without structural distress. The design of reinforced soil slopes is based on the use of limit equilibrium methods to evaluate both external (global) and internal stability of the structure. The required tensile strength of the reinforcements is selected during design so that the margins of safety, considering an internal failure similar to the one shown in Figure 27.4, are adequate. Guidance in soil reinforcement design procedures is provided by Mitchell and Villet (1987), Christopher et al. (1989), and Elias and Christopher (1997).

27.2.4 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 27.2, geotextiles are the geosynthetic product generally used in filtration. Both adequate hydraulic conductivity (provided by a geotextile with a relatively open 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 reduce excessively 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 plane of the geotextile over a service lifetime compatible with the application under consideration. Filtration concepts are well established in the design of soil filters, and similar concepts can be used in the design of geotextile filters.

The flow of liquid is perpendicular to the plane of the geosynthetic and, consequently, 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:

$$\psi = k_n/t$$

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 soil hydraulic conductivity. Some designers prefer to work directly with hydraulic conductivity and require the geotextile 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 filter the finer-sized particles and build up a stable upstream soil structure (Figure 27.5).

Several approaches 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.

Some of the soil particles will embed themselves on or 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 excessively clog. That is, the flow of liquid will not be decreased to a point at 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. Guidelines are available for clogging evaluation of noncritical, nonsevere cases, but laboratory testing is necessary in

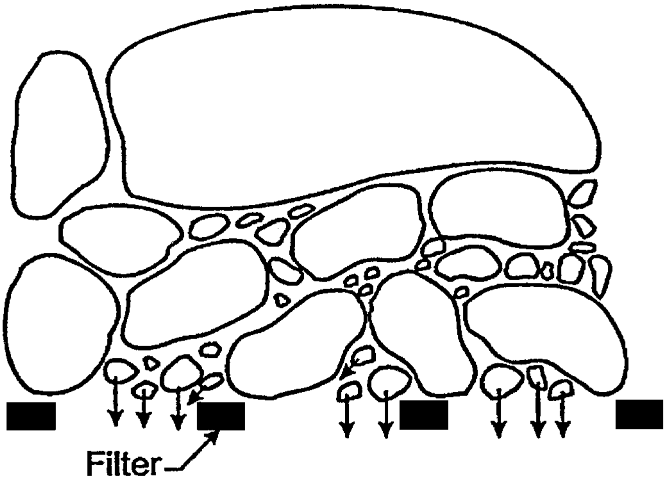


FIGURE 27.5 Geotextile providing adequate filtration through selection of adequate opening size.

important applications. Either the gradient ratio test (Haliburton and Wood, 1982), the long-term flow test (Halse et al., 1987), or the hydraulic conductivity ratio test (Williams and Abouzakhm, 1989) should be performed. An evaluation of the filtration function of geotextiles is provided by Christopher and Fischer (1992), Giroud (1996), Bhatia and Smith (1996a,b), Bhatia et al. (1996), and Holtz et al. (1997).

27.2.5 Drainage Function

Geosynthetics provide a drainage function by transmitting liquid within the plane of their structure. As shown in Table 27.2, 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 large amounts of liquid. 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.

Except for the consideration of flow direction, the soil retention and the long-term compatibility considerations regarding the drainage function of geosynthetics are the same as those discussed in Section 27.2.4 regarding the filtration function of geosynthetics. Since 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:

$$\theta = k_p \cdot t$$

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 geotextile, either when used as a drain itself or when placed onto a core to form a geocomposite must fulfill the filtration function. The compatibility of the soil with the geotextile filter must be ensured over the lifetime of the system being built. General references on design methods for the use of geosynthetics for drainage applications can be found in Holtz et al. (1997) and in Koerner (1994).

27.2.6 Infiltration Barrier Function

The infiltration barrier function can be performed by geosynthetic products that have hydraulic conductivity low enough to provide containment to liquid or vapor. As shown in Table 27.2, the infiltration 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/or temperature.

Geosynthetic barriers are commonly used as liners for surface impoundments storing hazardous and nonhazardous liquids, as covers above the liquid surface of storage reservoirs, and as liners 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 for base and cover liner systems of 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) from 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 generate 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 (1994).

27.2.7 Protection Function

Geosynthetics (mainly geotextiles) can be used to protect other 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 longer-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. Likewise, 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), Koerner et al. (1996), Narejo et al. (1996), and Wilson-Fahmy et al. (1996).

27.3 Geosynthetic Types

27.3.1 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 27.2 for many different geotechnical, environmental, and groundwater applications. For example, Figure 27.6 shows the con-

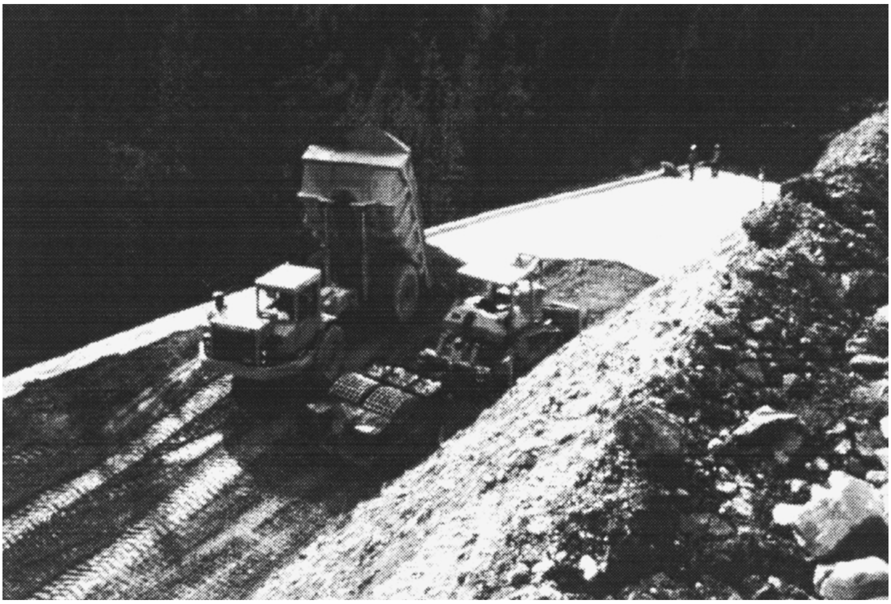


FIGURE 27.6 Placement of a high-strength nonwoven geotextile to perform a dual function of reinforcement and in-plane drainage in a reinforced slope.

struction of a reinforced slope in which geotextiles were selected as multipurpose inclusions within the fill, because 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., 1996).

Geotextiles are manufactured from polymer fibers or filaments which are later formed to develop the final product. Approximately 75% of the geotextiles used today are based on polypropylene resin. An additional 20% 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.

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

The fibers or yarns are formed into geotextiles using either woven or nonwoven methods. Figure 27.7 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 fabrics on a conveyor belt and subsequently bonding them by needle punching or 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 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

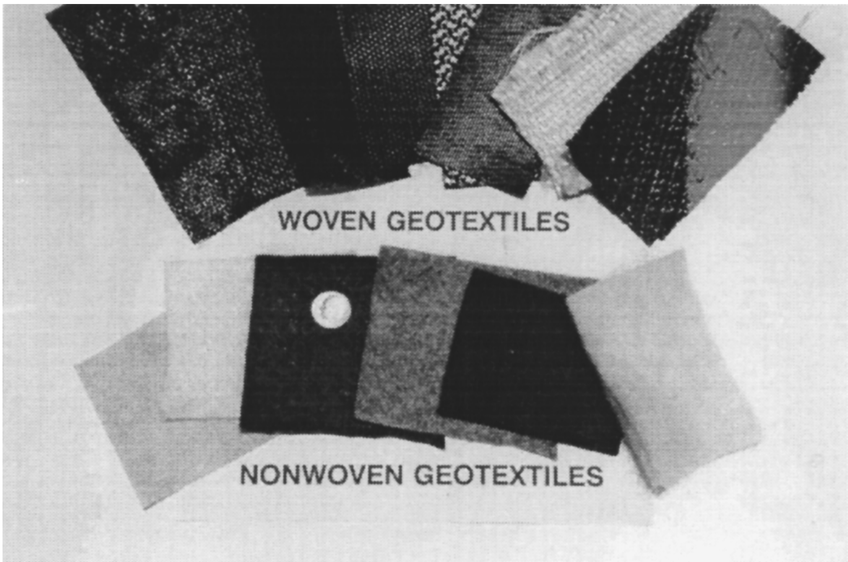


FIGURE 27.7 Typical woven and nonwoven geotextiles.

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 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 he or she specifies material properties important for the geotextiles' intended use. Table 27.3 describes the tests commonly performed in geotextile products (ASTM, 1995). Several of the reported material properties and test methods were borrowed from the textile industry. Consequently, several geotextile properties reported by manufacturers are index or quality control tests and are not intended for engineering design.

27.3.2 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), and reinforced chlorosulfonated polyethylene (CSPE). Figure 27.8 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 the 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 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 since it provides chemical resistance similar to that of HDPE but is more flexible and can more readily conform to underlying refuse settlements without puncturing.

TABLE 27.3 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	ASTM D 4595	Standard Test Method for Tensile Properties by the Wide-Width Strip Method
Multiaxial tensile or burst tests	ASTM D 3786	Standard Test Method for Hydraulic Bursting Strength of Knitted Goods and Nonwoven Fabrics — Diaphragm Bursting Strength Tester Method
Puncture resistance	ASTM D 4833	Standard Test Method for Index Puncture Resistance of Geotextiles, Geomembranes, and Related Products.
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

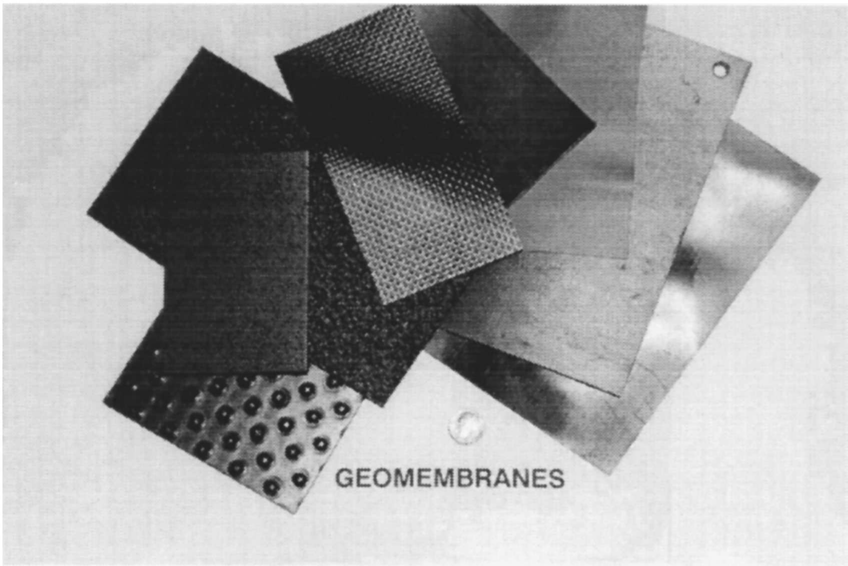


FIGURE 27.8 Typical geomembranes.

PVC geomembranes are used in liners for many waste containment applications, such as contaminated soils containment and liquid storage ponds. In the United States, PVC geomembranes have generally been recommended for relatively short-term applications, approximately 1 to 5 years, due to long-term durability concerns. 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 since 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 27.4. Geomembrane thickness ranges from 0.75 to 2.5 mm (30 to 100 mils). Table 27.5 summarizes the key performance factors related to 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.

TABLE 27.4 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. 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 often made with embedded reinforcing fabrics which affect tensile response.
Construction survivability	All three polymers have 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 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 which are relatively common, namely chlorinated solvents and hydrocarbons. PVC typically is the least chemically resistant of the three 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 significantly 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.

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. Extrusion welding and thermal fusion are the methods most commonly used, and are described next.

TABLE 27.5 Criteria for Selection of HDPE Geomembrane Thickness

Criteria	Considerations for Selection of Thickness
Abrasion resistance	The abrasion resistance of HDPE geomembranes increases with geomembrane thickness. Experience indicates that geomembranes with thickness less than [1 mm (40 mils)]may not have acceptable abrasion resistance.
Response to differential settlements	The thicker HDPE geomembrane have higher stiffness. This issue is more significant for geomembrane cover systems than for geomembrane 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 (80 mils) is desirable.
Effective welding	The thinner the HDPE geomembrane, the more difficult is the welding of adjacent panels. For most effective welding, a thickness of at least 1 mm (40 mils) is desirable, and 1.5 mm to 2 mm (60 to 80 mils) is preferred.

Extrusion welding is presently 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.

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 since 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 27.9).

The material properties of geomembranes are divided into the properties of the raw polymer or resin used in manufacture of the geomembrane sheet and the manufactured geomembrane properties. Table 27.6 lists the tests commonly performed for evaluation of the raw polymer properties. Table 27.7 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.

27.3.3 Geogrids

Geogrids constitute a category of geosynthetics designed preliminarily 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 polyester and coated polyester geogrids are typically woven or knitted. Coating is generally performed using PVC or acrylics to protect the filaments from construction damage. The polypropylene geogrids are either extruded or punched sheet drawn, and polyethylene geogrids are exclusively punched sheet drawn. Figure 27.10 shows a number of typical geogrid products.

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 waterproofing 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. A relatively new

FIGURE 27.9 Monitoring seaming of a geomembrane liner.

TABLE 27.6 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)	ASTM D 4595	Thermogravimetric analysis (TGA) Differential scanning calorimetry (DSC) Thermomechanical analysis (TMA) Infrared spectroscopy (IR) Chromatography (GC) Gel permeation chromatography (GPC)

application for geogrids is 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. Since 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 tensile strength, which is typically reported from wide-width tensile tests (ASTM D 4595). The wide-width tests are 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 safety factors for installation damage, creep deformation, chemical degradation, and biological degradation. The partial factors of safety for installation damage, chemical degradation, and biological degradation

TABLE 27.7 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 412	Test Method for Rubber Properties in Tension
Tensile behavior	ASTM D 638	Standard Test Method for Tensile Properties of Plastics
Tensile behavior	ASTM D 882	Test Methods for Tensile Properties of Thin Plastic Sheeting
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
Environmental stress crack	ASTM D 1693	Standard Test Method for Environmental Stress-Cracking of Ethylene Plastics
Environmental stress crack	ASTM D 2552	Environmental Stress Rupture of Type III Polyethylene Under Constant Tensile Load
Carbon black	ASTM D 1603	Standard Test Method for Carbon Black in Olefin Plastics
Carbon black	ASTM D 3015	Standard Practice for Microscopical Examination of Pigment Dispersion in Plastic Compounds
Seam strength	ASTM D 4437	Standard Practice for Determining the Integrity of Field Seams Used in Joining Flexible Polymeric Sheet Geomembranes

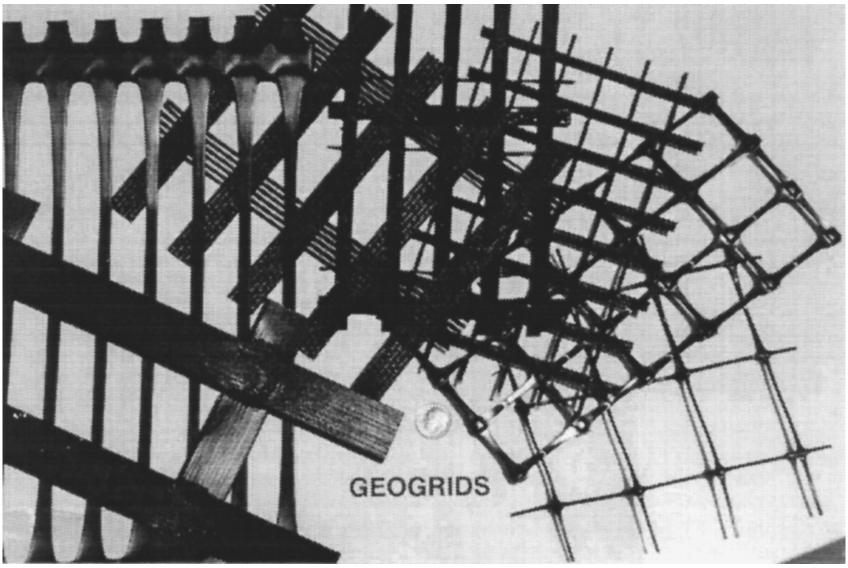


FIGURE 27.10 Typical geogrids.

range from 1.0 to 1.6, with the partial factor of safety for creep ranging from 1.5 to 3.5 (Koerner, 1994). Manufacturers typically provide recommendations for the allowable tensile strengths of their products.

27.3.4 Geosynthetic Clay Liners (GCLs)

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 which are joined in the field by overlapping. They are generally used as an alternative to compacted clay liners.

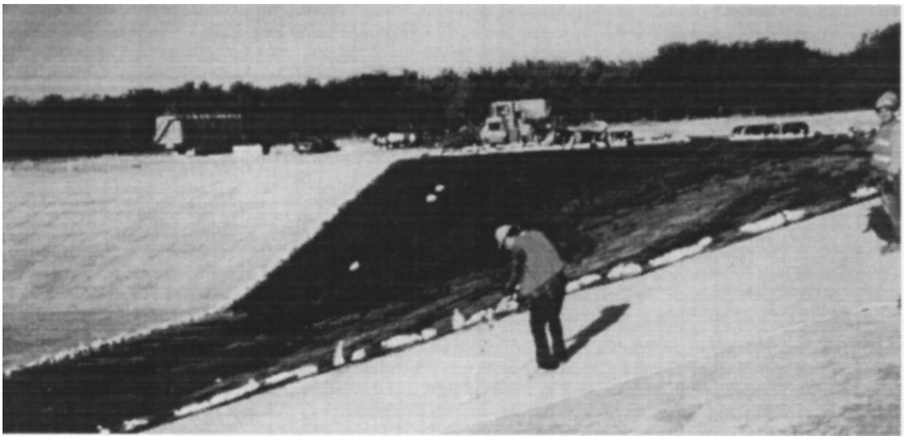


FIGURE 27.11 Installation of a GCL during construction of a landfill base liner.

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 27.11).

Some advantages of GCLs over compacted clay liners 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. Moreover, since 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 27.12): bentonite sandwiched between two geotextiles or bentonite glued to a geomembrane. The primary purpose of the geosynthetic component 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 the use of 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/s. Infiltration under unit hydraulic gradient through a material with hydraulic conductivity of 1×10^{-9} cm/s would result in an infiltration rate of 0.3 mm per year.

Since 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 27.3.1. 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,

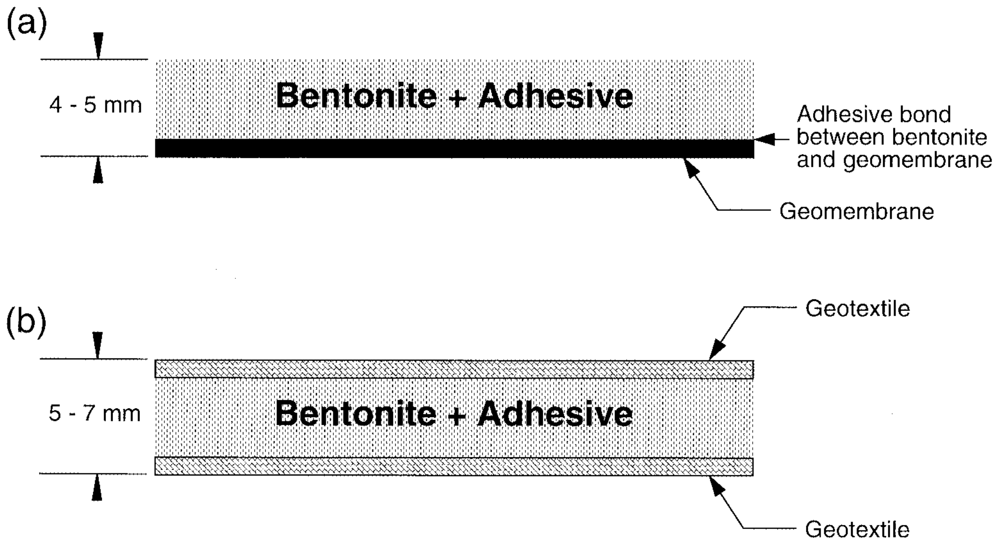


FIGURE 27.12 Typical GCL configurations: (a) bentonite glued to a geomembrane; (b) bentonite sandwiched between two geotextiles.

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.

27.3.5 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 27.3.6.

Geocomposite sheet drainage systems have been engineered to replace costly aggregate and/or 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 structures of the core drainage products range from a dimpled core to a geonet. Geonets, a commonly used drainage product, generally consist of two 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 liquids or gases. Figure 27.13 shows a number of geonets currently available in the market.

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 needle-punched nonwoven geotextile used as a protective material for the underlying geomembrane, while the top geotextile may be a thinner

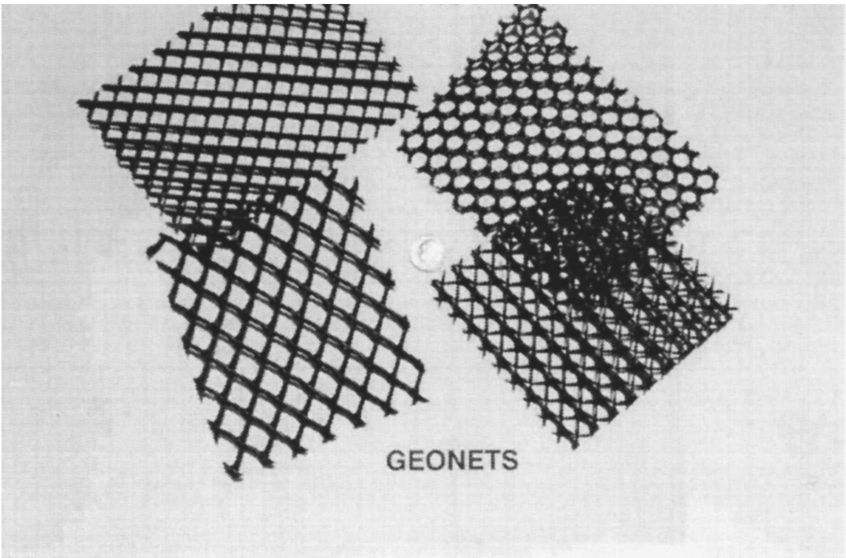


FIGURE 27.13 Typical geonets used as the core of geocomposite sheet drains.

FIGURE 27.14 Typical geocomposite sheet drains.

nonwoven or woven product. Composite drainage nets are typically formed by thermally bonding the geotextile and geonet. Glueing 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 27.14 shows a number of available geocomposite sheet drainage materials.

Since the purpose of the core is drainage, the most important properties to include in specifications are thickness, crush strength, and transmissivity under load. Table 27.8 summarizes the tests commonly performed to evaluate the properties of geocomposite sheet drains. It is also important to evaluate filtration requirements for the geotextile. Design of geocomposite drains is covered by Holtz et al. (1997).

TABLE 27.8 Standard Tests for Geocomposite Drainage Nets

Property	Test Standard	Test Name
Thickness	ASTM D 5199	Standard Test Method for Measuring Nominal Thickness of Geotextiles and Geomembranes
Crush strength	ASTM D 1621	Standard Test Method for Compressive Properties of Rigid Cellular Plastics
Transmissivity	ASTM D 4716	Standard Test Method for Constant Head Hydraulic Transmissivity (In-Plane Flow) of Geotextiles and Geotextile Related Products

27.3.6 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 pore water pressure-induced flow. They are placed vertically through high water content silts and clays to produce short 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. Now, 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 but usually extend to the bottom of the soft layer(s). 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 pressures in the underlying soil. The pore water pressures are 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 since 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. Since their flow capacity is usually adequate, selection of the spacing 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, the geotextile covering or wrapping serves primarily a filtration function. 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 "lances" or mandrels) for insertion to the desired depth. The bottom of the lance should be covered by an expendable shoe which 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 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 covered in Holtz et al. (1997).

27.3.7 Geocells

Geocells (or cellular confinement systems) are three-dimensional, expandable panels made from HDPE or polyester strips. 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 27.15). This creates a system that holds the infill material in place and prevents mass

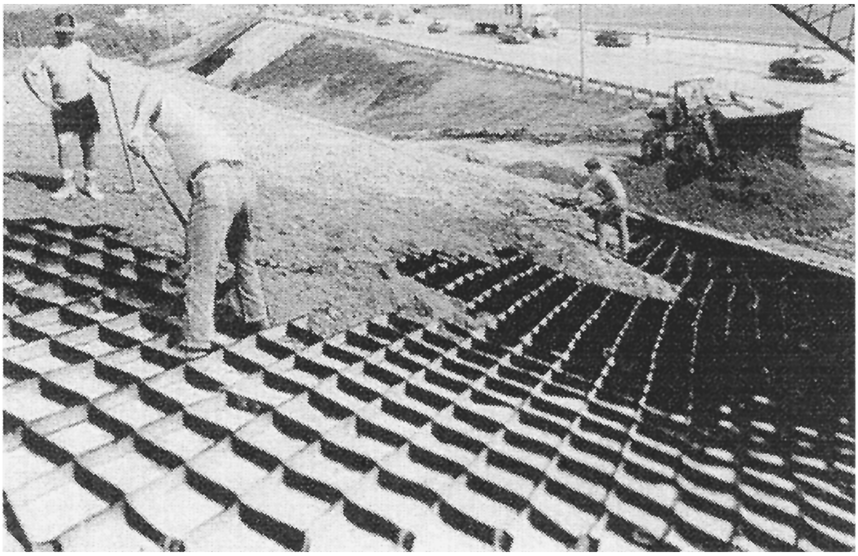


FIGURE 27.15 View of expanded geocell. (Photo courtesy of Presto Products Company.)

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 on the subgrade surface and propped open in an accordion-like fashion with an external stretcher assembly. They are then generally filled with sand (although other infill materials can be selected) 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 a confined condition. 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 loads.

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.

27.3.8 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

FIGURE 27.16 Erosion control mat placed to help establish the vegetation on the face of a 1H:1V reinforced soil slope.

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 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 geocell products with concrete infill, vegetated concrete block systems, and fabric-formed revetments.

Figure 27.16 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 27.16) by stapling or pinning them to the soil surface. Intimate contact between the blanket or mat and the soil is very important since water flow beneath the material has usually been the cause of poor functioning.

27.3.9 HDPE Vertical Barrier Systems

The use of geomembranes (Section 27.3.2) 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 because of 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 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.

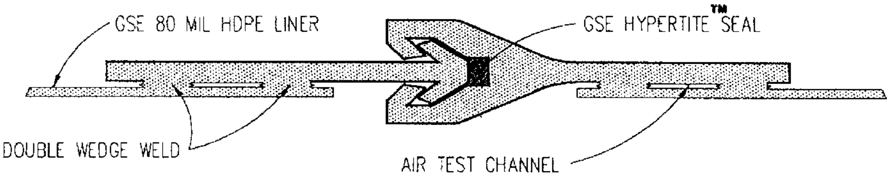


FIGURE 27.17 Interlocking system for HDPE vertical barriers. (Figure courtesy of GSE Lining Technology, Inc.)

Since 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 using chloroprene-based, hydrophilic seals. Figure 27.17 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 8 times its original volume when exposed to water. These interlocking HDPE vertical barrier systems have become 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/or chemicals.

An additional advantage of the HDPE vertical barrier system is that both a containment and a collection system (e.g., a geocomposite sheet drain) 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 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. 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 m and 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 27.5 .

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. Special trencher equipment can install a vertical geomembrane wall with a collection system consisting of HDPE pipe and a gravel fill in one trench, in one pass. Figure 27.18 shows the placement of an HDPE panel using this one-pass deep trencher.

27.4 Geosynthetic Applications in Landfill Design

The multiple use of geosynthetics in the design of modern municipal solid waste landfills is a good illustration of an application in which the different geosynthetics can be and have been used to perform all the functions discussed in Section 27.3. Virtually all the different types of geosynthetics discussed in Section 27.4 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 of a couple of millimiters in thickness can provide performance equivalent to a soil infiltration barrier of sometimes several meters in thickness.

Landfill base liners are placed below the waste in order 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, of 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

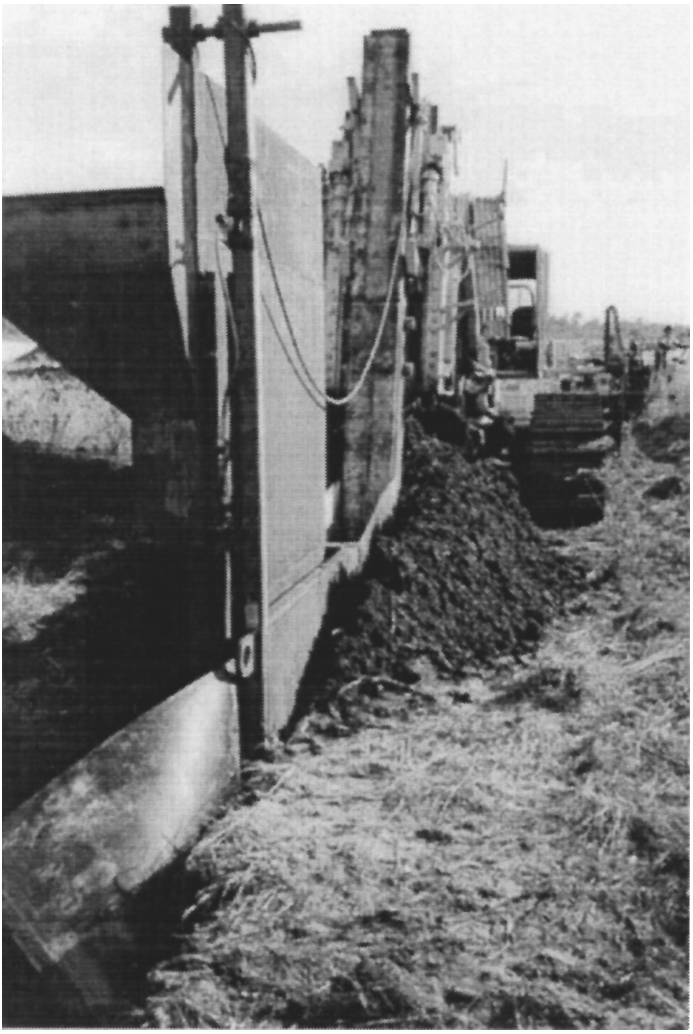


FIGURE 27.18 One pass trencher for installation of an HDPE vertical barrier system. (Photo courtesy of Groundwater Control, Inc.)

leachate. Waste containment systems employ geosynthetics to varying degrees. Figure 27.19 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 27.19 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 the 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

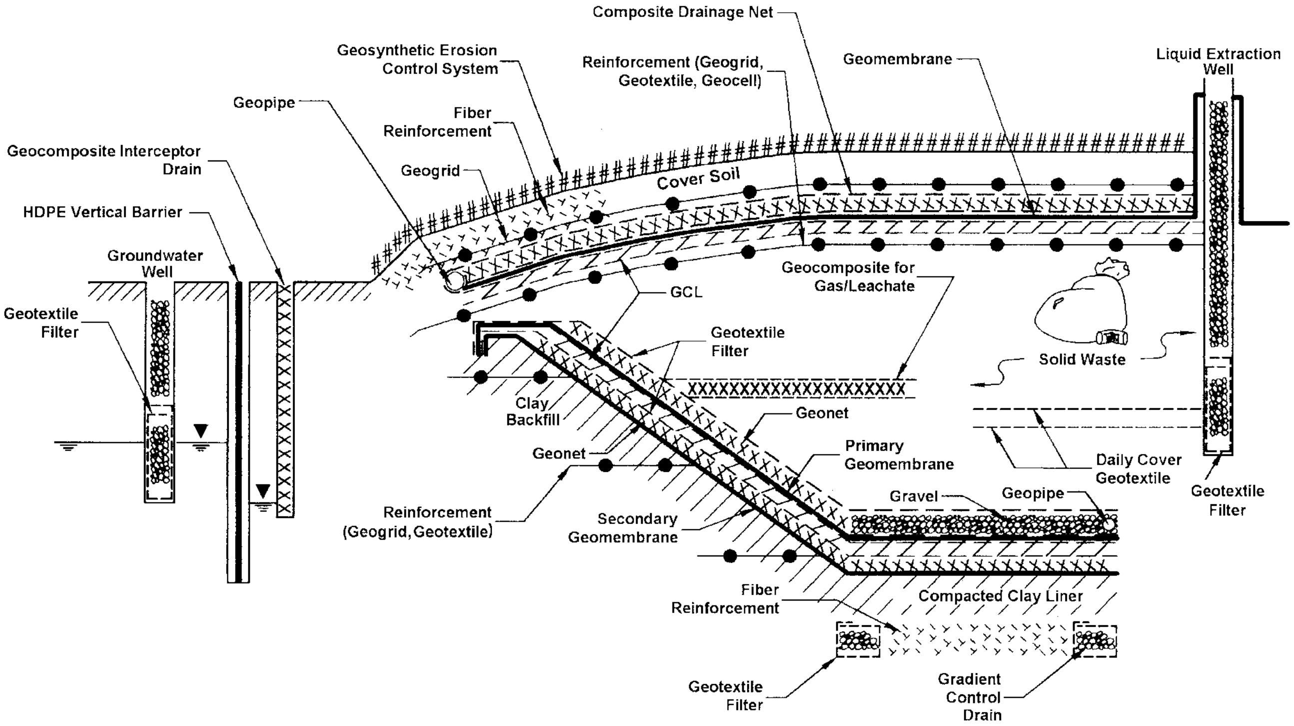


FIGURE 27.19 Multiple use of geosynthetics in landfill design.

gradient control drains built using geotextile filters. Moreover, the foundation soil below the bottom of the landfill may be stabilized as shown in the figure using randomly distributed fiber reinforcements, while the steep side soil slopes beneath the liner could also be reinforced using geogrids. Different types of geosynthetics (e.g. geogrids, geotextiles, fibers) could have been selected for stabilization of the foundation soils.

The cover system of the landfill illustrated in Figure 27.19 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 27.19 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. 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 illustrated in the figure. Finally, the figure shows the use of an 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 27.19 would normally be needed at any one landfill facility, the figure illustrates the many geosynthetic applications that can be considered in landfill design.

27.5 Case History of Vertical Barrier System

Although the use of geosynthetics in many geotechnical and environmental projects is related indirectly 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 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 meters. During years of operation and the subsequent closing of the manufactured gas plant, some process residuals migrated to subsurface soils and groundwater. Over time, the presence of coal tar-like material in the form of dense nonaqueous phase liquid (DNAPL), was observed seeping from the bank of the Codorus Creek. DNAPL was also noted in some monitoring wells on site.

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 Codorus Creek, which was considered not to be feasible 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 27.17). HDPE panels were keyed into soil improved by jet grouting, 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 of (Figure 27.20).

FIGURE 27.20 Installation of HDPE barrier wall utilizing conventional pile driving equipment. (Photo courtesy of Groundwater Control, Inc.)

In order 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 the high pressure injection of a cement and bentonite slurry horizontally into the soil strata in order to improve its mechanical and hydraulic properties. The containment wall was approximately 290 m in length. The soils 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 predrilled 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 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.

For Further Information

Koerner (1994) provides an excellent, well-illustrated overview of the different types of geosynthetics and their applications.

Holtz, Christopher, and Berg (1997) 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, 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. Particularly, the proceedings of conferences organized by the North American Geosynthetics Society (NAGS) every two years are an important source. 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, providing product-specific properties, suggested design methods, and recommended safety factors.

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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 which 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 which 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. Removal of particle 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/or 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 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 material as an integral part of a man-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 man-made 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/or 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 man-made 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 of 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 which 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 which 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 to amount of material per unit area (units are oz/yd^2 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 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 into 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 terephthalic 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, 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 which have been spun (extruded), drawn, laid into a web and bonded (chemical, mechanical, or thermal bonding) together in one continuous process.

Staple Fibers Fiber of short lengths frequently used to make needle-punched 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 Geotextile A 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 is 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 (1994).