22 GEOSYNTHETICS IN GEOTECHNICAL ENGINEERING

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22.1 INTRODUCTION

Geosynthetics are a rapidly emerging family of materials used in geotechnical engineering in a wide variety of applications. They are almost exclusively polymeric and consist of the following major types (Koerner, 1990):

- Geotextiles
- Geogrids
- Geonets
- Geomembranes
- Geocomposites

When following the concept of "design-by-function" (Koerner, 1984) one must decide on a primary function for the specific application considered and select the appropriate type of geosynthetic; see Table 22.1 for the various options available. It should be noted that within each type of geosynthetic listed in Table 22.1 there exists a tremendous variety of product styles and configurations, which will be described in the sections to follow. Since the literature is abundant on product applications, design concepts will be emphasized throughout.

22.2 GEOTEXTILES

22.2.1 Overview

Geotextiles are porous, flexible polymeric fabrics made to serve one or more of the functions listed in Table 22.1. Most are made from polypropylene or polyester, but specialty situations sometime require other polymers, for example, polyethylene or polyaramide. The basic resins are usually augmented by anti-degradants (such as carbon black) and other fillers and/or additives and made into fibers. These fibers take the shape of monofilaments, monofilament yarns (multifilaments), staple yarns, and slit or split films (or tapes). The fibers are then made into fabrics of which woven and nonwoven styles dominate; see Figure 22.1. Very few are knitted fabrics. The resulting series of options available to a geotextile manufacturer leads to a tremendous variety of available products; see Table 22.2 for a listing of commercially available products. The possibility always exists for developing specialty products as well.

Consideration of the above range of available geotextiles should dispel any notion of a design or specification based on a "product *x* or equal" concept. No two geotextiles are truly "equal" and design and selection must be based on a rational

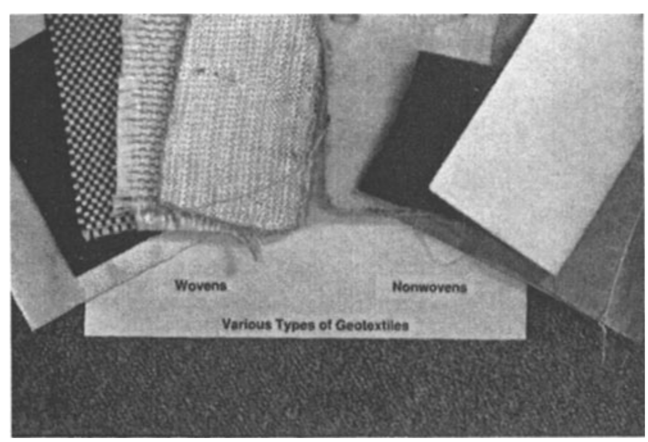


Fig. 22.1 Photographs of various geotextiles.

TABLE 22.1 GEOSYNTHETIC TYPE VERSUS AVAILABLE FUNCTION.

Type	*Available Functions*				
	Separation	*Reinforcement*	*Filtration*	*Drainage*	*Moisture Barrier*
Geotextile	P or S	P or S	P or S	P or S	n/a
Geogrid	S	P	n/a	n/a	n/a
Geonet	S	n/a	n/a	P	n/a
Geomembrane	S	n/a	n/a	n/a	P
Geocomposite	P or S	P or S	P or S	P or S	P or S

Note: P = primary function; S = secondary function; n/a = not applicable.

H.-Y. Fang (ed.), *Foundation Engineering Handbook*

TABLE 22.2 APPROXIMATE NUMBER OF COMMERCIALLY AVAILABLE GEOTEXTILES.

Region	*Manufacturers*	*Number of Types of Available Geotextiles*
U.S.A.	50	450 +
Canada	10	70
Europe	30	150 +
Australia / New Zealand	10	40
South and Central America	10	50
Asia	15	70
Africa	5	30
Total	130	860 +

approach. Such an approach is embodied in the design-by-function concept. At the heart of this concept is the formulation of a factor of safety in the traditional engineering manner, that is,

$$\text{F.S.} = \frac{\text{allowable (or test) value}}{\text{required (or design) value}} \tag{22.1}$$

where F.S. must be greater than 1, the actual magnitude depending upon the implication of failure, which is always site-specific.

Regarding the allowable (or test) value for the various properties of geotextiles, there is a large amount of worldwide activity. At least 30 organizations are working on geotextile test methods and standards. In the U.S.A., the American Society of Testing and Materials (ASTM) is the lead organization, which has grouped their activity into physical, mechanical, hydraulic, endurance, and durability categories. Included in each group are index (or comparison and quality control oriented) tests and performance (or design oriented) tests, the latter being preferred for engineering design. Rather than describe all of the available tests, only those relevant to the designs presented in this chapter will be described and referenced. Furthermore, they will be described and explained when they are needed and not as a separate section.

Regarding the required (or design) value in the factor of safety equation, geotechnical engineering procedures will generally be required. In reinforcement problems this will require an analysis of stress and strain, while in hydraulic problems this will require estimates of flow and soil retention considerations. In some cases, altogether new concepts will be required.

The subsections to follow in this geotextile section are written to conform to the major functions that geotextiles can perform; recall Table 22.1. Each will be treated speparately with a descriptive problem illustrating the type of application involved in the utilization of the particular function.

22.2.2 Geotextiles in Separation

While there are many applications where geotextiles can be used to separate two dissimilar materials, their use beneath pavement stone-base courses and above the underlying soil subgrade is very common. The objective is to keep the stone from penetrating into the soil and the soil from intruding into the stone. By so doing, the drainage capability of the stone base is preserved for the lifetime of the pavement. This drainage preservation is a significant feature in pavement lifetime, particularly with fine-grained soil subgrades or in areas of cold weather where freeze–thaw cycling occurs.

Presented in Koerner (1990) are four separate design situations, but only one will be illustrated here. As shown in Figure 22.2, the pressure exerted from the heaviest loaded vehicle will induce stress in the geotextile, causing the underlying soil to protude up into the void created by adjacent stone particles. Thus, there is a tendency for the geotextile to burst in an out-of-plane manner. The following factor-of-safety equation approximates the situation:

$$\text{F.S.} = \frac{p_t d_t}{p_a d_v} \tag{22.2}$$

where

p_t = burst test pressure of candidate geotextile
d_t = diameter of test device
p_a = maximum applied pressure
d_v = diameter of stone aggregate void

Using a Mullen burst test method (ASTM D774) where $d_t = 30.5$ mm and $d_v = 0.4\ d_a$ (where d_a = diameter of the

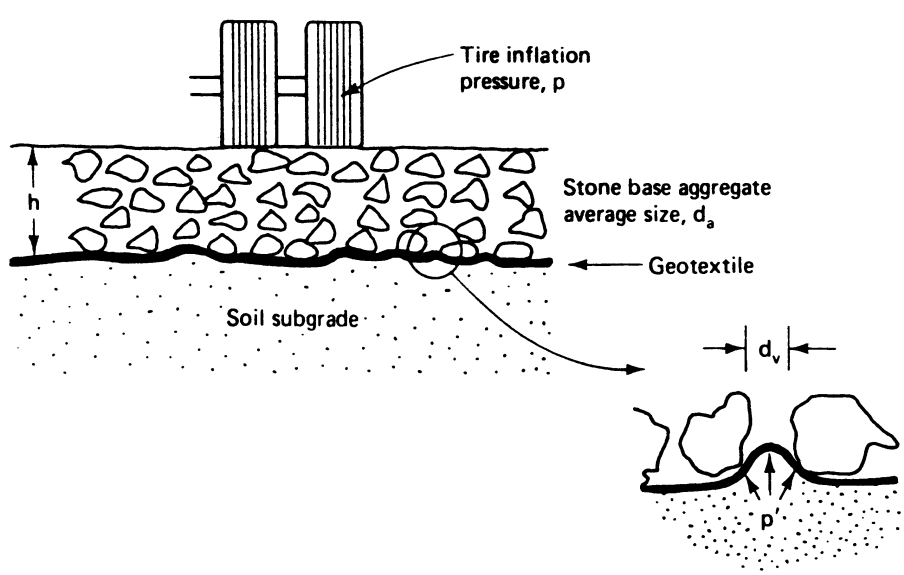


Fig. 22.2 Detail used in burst analysis.

aggregate), a more general equation can be developed:

$$\text{F.S.} = \frac{p_t(30.5)}{p_a(0.4\,d_a)} \tag{22.3}$$

$$\text{F.S.} = \frac{76.2\,p_t}{d_a p_a} \tag{22.4}$$

where d_a must be in millimeters and the units of p_t and p_a must be the same. Thus for 75-mm aggregate, a maximum pressure of 550 kPa and a candidate geotextile having an allowable burst strength of 2000 kPa, the resulting factor of safety is 3.7. Other problems involving grab strength, puncture resistance, and impact resistance can also be formulated. They all illustrate the concept of design by function.

22.2.3 Geotextiles in Reinforcement

Geotextiles having varying degrees of tensile strength can obviously be used to reinforce soil, which is notoriously weak in tension. Geotextile reinforcement of unpaved roads on very weak soil subgrades (e.g., CBR < 2) has nicely illustrated this feature (see Hausmann, 1986, for a review of various analytic techniques). Other areas of considerable activity are geotextile-reinforced walls (Yako and Christopher, 1987) and stabilization of existing slopes (Koerner and Robins, 1986). Nowhere, however, is there greater activity than in the construction of embankments over extremely soft soils. This work, pioneered by the U.S. Army Corps of Engineers, has produced remarkable results (Fowler and Koerner, 1987). River-transported fine-grained soils of near zero shear strength have been used as embankment foundation material when supported by a high-strength geotextile. Often, these embankments are used for subsequently dredged soil containment dikes or for building directly thereon. A recent conference has been directed at this activity (Koerner, 1988).

At the heart of the analysis is a limit equilibrium method modified for the inclusion of a geotextile. As illustrated in Figure 22.3, a traditional slope stability procedure using undrained shear strengths can be used. For moment equilibrium considerations,

$$\text{F.S.} = \sum \frac{\text{resisting moments}}{\text{driving moments}} \tag{22.5}$$

$$\text{F.S.} = \frac{(\tau_e L_{ab} + \tau_f L_{bc})R + T_a Y}{wX} \tag{22.6}$$

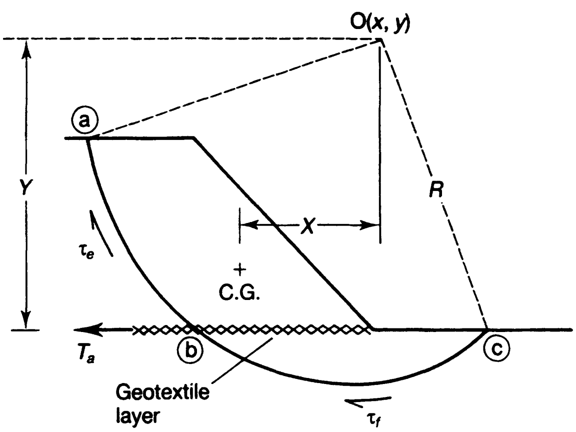


Fig. 22.3 General configuration used to modify slope stability analysis to include a geotextile reinforcement layer.

where

τ_e = shear strength of embankment soil (often neglected owing to lack of confinement or low strength)
L_{ab} = arc length a–b
τ_f = shear strength of foundation soil (usually very low)
L_{bc} = arc length b–c
R = radius from critical center to failure arc
T_a = allowable tensile strength of geotextile
Y = moment arm of geotextile (sometimes taken as R)
w = weight of soil in failure zone
X = moment arm from center of gravity to center of failure arc

It is easily seen in the above equation that the geotextile's strength can be increased as necessary to drive the factor of safety up to an acceptable value. Strengths of up to 500 kN/m have been used to date. Note that these strengths must be tested in a plane strain condition, the closest simulated test being the wide-width tensile test (ASTM D4595-86). This test uses a test specimen 200 mm wide by 100 mm in height and loads it at a constant strain rate until failure. Also, note that fabric creep must be allowed for; thus, the ultimate strength must be somewhat reduced. Considering that a strength gain in the underlying foundation soil will generally occur, a creep factor of safety of 1.5 to 2.5 should generally be adequate. Other considerations that are important to consider in design are sewn-seam requirements, the effect of holes (e.g., when vertical strip drains are installed), manner of fill placement, required fabric modulus, friction between fabric and embankment soil, and anchorage length (Fowler and Koerner, 1987; Koerner, 1988). The point that should be emphasized, however, is that with the advent and use of high-strength geotextiles we can almost "build on water."

22.2.4 Geotextiles in Filtration

There are myriad applications for geotextiles used as filters, for example, underdrains, behind retaining walls, as capillary breaks, etc. Geotextiles used in soil as filters for liquids must fulfill two mutually contradicting requirements. The first is that the fabric voids must be sufficiently open to allow the liquid to pass through without building excess pore water pressure, while the second is that the fabric voids must be sufficiently tight to prevent excess loss of upstream soil particles. Superimposed upon both is the requirement that the soil must not clog the fabric, thereby blocking flow. The first requirement of adequate flow is handled by forming a factor of safety in the form of a permittivity comparison, that is,

$$\text{F.S.} = \frac{\psi_{\text{allow}}}{\psi_{\text{req}}} \tag{22.7}$$

where permittivity ψ is defined as

$$\psi = \frac{k_n}{t} \tag{22.8}$$

and k_n is coefficient of permeability normal to the fabric, and t is the fabric thickness. This term is necessary owing to the sensitivity of fabric thickness, which varies under applied normal load, hydraulic gradient, etc. The fabric's allowable permittivity value is obtained from a laboratory permeability test (ASTM D4491), either with the fabric unloaded or, better, loaded; see Table 22.3 for typical values. The required permittivity value is estimated or designed using a form of Darcy's equation. The latter approach is generally preferred where flow net techniques are often required; see Koerner (1990) for examples.

TABLE 22.3 TYPICAL PERMITTIVITY AND PERMEABILITY VALUES OF GEOTEXTILES.

Fabric Type	*Permittivity* (s^{-1})	*Permeability* (cm/s)
Woven, monofilament	1000 to 0.1	10 to 0.01
Nonwoven, needle-punched	50 to 0.1	1 to 0.01
Nonwoven, heat-set	10 to 0.1	0.1 to 0.005
Nonwoven, resin-bonded	1 to 0.005	0.05 to 0.001
Woven, slit film	1 to 0.01	0.01 to 0.001

The second mechanism of soil retention is handled by comparing the fabric's opening size to the size of the soil to be retained. Some form of the following relationship is usually used:

$$O_f = \lambda d_s \tag{22.9}$$

where

O_f = opening size of the fabric (often taken as the 95 percent opening size)
d_s = diameter of soil to be retained (often taken as the 85 percent finer size)
λ = function of soil gradation, soil density, liquid type, hydraulic gradient, etc.

In its simplest form, Carroll (1983) has suggested,

$$O_{95} < (2 \text{ or } 3) \times d_{85} \tag{22.10}$$

However, numerous other more detailed approaches are also available; see Bertacchi and Cazzuffi (1985) in this regard.

The third consideration is that undue clogging (short-term or long-term) of the geotextile must not occur. In discussing clogging one must consider how a geotextile filter works. Essentially, the geotextile represents a catalyst that is intended to force the upstream soil to do its own filtering. Obviously, some of the fine soil particles directly againt the fabric will be lost through, or within, the fabric, but the amount must not be excessive. During this action the soil should be "tuning" itself to come into equilibrium with the applied flow regime. Many postulated mechanisms have been presented (McGown, 1978). As a check, laboratory testing may also be performed. Two options are currently available. One is the gradient ratio test (Haliburton and Wood, 1982), which measures the hydraulic gradient of flow through the fabric plus 25 mm of soil and compares this value to the hydraulic gradient through 50 mm of soil by itself. If this ratio is greater than 3.0, the candidate fabric–soil combination is not compatible. If it is less than 3.0, clogging should not occur. The test was originally developed to evaluate cohesionless soils and woven monofilament fabrics. For other soils and/or fabrics, the test is not well behaved (Halse et al., 1987). This leads to the second option for evaluating soil–fabric compatibility, which is the long-term flow test (Koerner and Ko, 1982). Here the site situation is simulated as closely as possible, that is, in terms of soil type, fabric, hydraulic conditions, etc., and long-term flow is measured in constant-head column tests. Typical response curves are shown in Figure 22.4. The initial decrease in flow is due to soil densification and is not meaningful. From the transition time on, however, the response is very significant. If the flow rate continues to decrease, clogging is occurring and the situation is not acceptable. If, however, the flow rate stabilizes, the soil–fabric combination has accommodated the flow regime and hydraulic equilibrium has been achieved. Intermediate situations call for continued testing, which can take up to 10 000 hours (approximately one year).

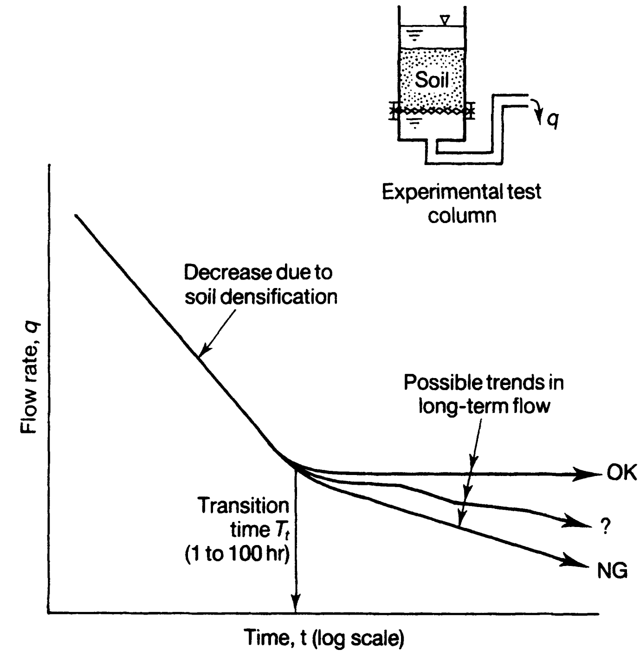


Fig. 22.4 Flow rate response curves for assessing soil–fabric clogging potential.

22.2.5 Geotextiles in Drainage

When geotextiles are used as drains as in chimney drains, fin drains, embankment drains, etc., the flowing liquid moves within the plane of the fabric. All fabrics possess this capability but to widely varying degrees. See Table 22.4, where the term *transmissivity* (as described below) will be used to describe in-plane flow. For reference purposes, the traditional permeability coefficient is also given in Table 22.4.

$$\theta = k_p t \tag{22.11}$$

where

θ = transmissivity
k_p = planar coefficient of permeability
t = fabric thickness

The design of geotextile drains follow along similar lines to that for geotextile filters. The specific elements are adequate flow, soil retention, and soil–fabric compatibility. The only difference is in the first part, adequate flow, which is determined on the basis of the previously defined transmissivity, and is used as follows:

$$\text{F.S.} = \frac{\theta_{allow}}{\theta_{req}} \tag{22.12}$$

where

θ_{allow} = allowable (or test) value of the geotextile
θ_{req} = required (or design) value

The allowable transmissivity value is determined from a laboratory test of either radial or planar in-plane flow configuration (Koerner and Bove, 1983). The results are strongly dependent on the applied normal pressure and can be made to simulate in-situ conditions quite closely (ASTM D4716). As suggested from Table 22.4, considerable data is available. The value of required transmissivity (the denominator of Equation 22.12) is determined by geotechnical design methods that usually require use of Darcy's formula, either directly or

TABLE 22.4 APPROXIMATE RANGE OF VALUES FOR GEOTEXTILE TRANSMISSIVITY.

Fabric Type	Transmissivity ($m^3/s \cdot m$)	Permeability Coefficient (cm/s)
Woven, slit film	1.5×10^{-9}	0.001
Nonwoven, heat-set	3.0×10^{-9}	0.002
Woven, monofilament	2.0×10^{-8}	0.015
Nonwoven, resin-bonded	7.0×10^{-8}	0.02
Nonwoven, needled (thin)	2.0×10^{-6}	0.3
Nonwoven, needled (medium)	10.0×10^{-6}	0.8
Nonwoven, needled (heavy)	20.0×10^{-6}	1.0

by means of a flow net. Other design guides may also be used (Koerner, 1990).

22.2.6. Geotextiles as Moisture Barriers

By infiltrating the voids of a geotextile with bitumen, polymer, or other filter, a moisture barrier can be created. This procedure has advantages in certain applications but rarely creates a complete geomembrane of the type to be discussed in the geomembrane section. In applications where the properties of a geotextile are important (e.g., tensile strength, puncture resistance, impact resistance, etc.) and yet some moisture release from the system is permitted, the technique has been utilized. These include water-reservoir liners, where some leakage is tolerable, and membrane-encapsulated soil layers (MESLs). This latter concept is used where a moisture-sensitive subgrade or subbase soil is fully encapsulated (bottom, sides, and top) within a bitumen-infilled geotextile. The preservation of the as-placed moisture content of the encapsulated soil is maintained, thereby providing temporary stability (Koerner, 1990).

Other than for these relatively limited applications, however, the function of a geosynthetic moisture barrier is best provided by a geomembrane that will be discussed separately later in the chapter.

22.3 GEOGRIDS

22.3.1 Overview

Geogrids are deformed or nondeformed netlike polymeric materials used in geotechnical engineering-related construction activities for reinforcement; see Figure 22.5. Their primary function is reinforcement; however, they sometimes can be used for separation of large-sized particles as well. It should be noted that geogrids are *not* geonets, which are used exclusively as drainage cores and will be treated separately in the next section.

There are a wide variety of manufacturing approaches used to make geogrids and hence their final shapes vary considerably. Furthermore, the area is quite active and new products are appearing regularly. The original geogrids utilize a geomembrane sheet with holes punched into it at regular spacings. The sheet is then cold-worked over a series of rollers that are successively moving faster, stretching the product as it travels along. The original holes become ellipses when the final product, with approximately an 8-to-1 draw ratio, is completed. Thus, the polymer, which is high-density polyethylene, is mechanically drawn well beyond its yield point, thereby providing enhanced modulus, strength, and creep resistance. A related product is biaxially deformed, providing a geogrid with balanced strength

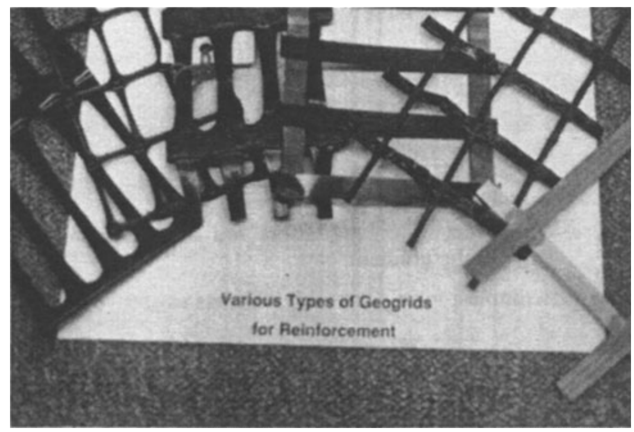


Fig. 22.5 Photographs of commercially available geogrids.

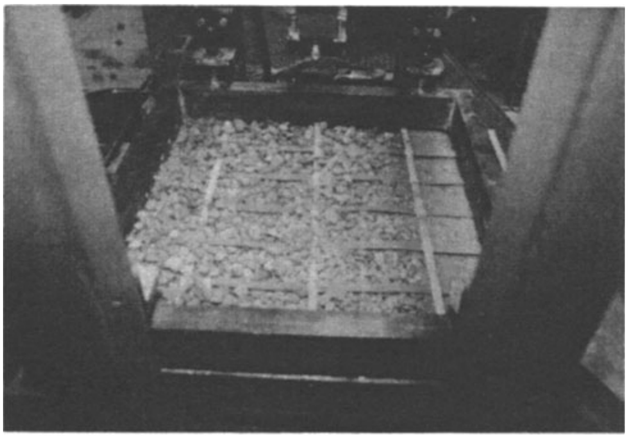
properties in two perpendicular directions. A similarly manufactured product is made by mechanically drawing the punched sheets by gripping the transverse ribs and elongating the longitudinal ribs.

Geogrids are also available from bonding of mutually perpendicular high-strength polymer strips together at their cross-over points, or nodes. One company uses high-tenacity polyester strips, which are ultrasonically bonded at their nodes, while a different firm's are melt-bonded at their nodes. In this latter case it is the polypropylene sheathing covering the high-tenacity polyester fibers that is melt-bonded.

A number of different geogrids are also manufactured by entangling high-strength polyester yarns at their intersections (or nodes), thus providing a gridlike material. A surface coating is used to maintain the gridlike shape. The actual processing can be done in a variety of ways.

22.3.2 Properties of Geogrids

Since the primary function of geogrids is in soil reinforcement, their tensile strength plays a critical role. This strength is usually assessed in a wide-width test or on the basis of individual rib strength if the ribs are spaced widely apart. The result is best expressed in force per unit width dimensions, which is the necessary value for plane-strain-related problem solutions. Note, however, that this ultimate value must be reduced for long-term creep considerations by a suitable factor of safety. This value is between 2.0 and 4.0 depending upon the type of polymer, manufacturing style, design lifetime, and criticality of structure. Installation damage and long-term degradation should also be considered.



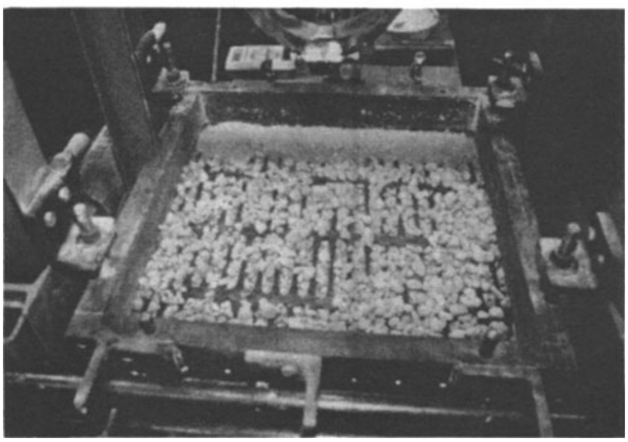


Fig. 22.6 Geogrids with stone embedded within structure.

Also of significance is junction, or node, strength. This is due to the functioning of the geogrid when it is being stressed in a soil system. Since the soil has complete strike-through of the geogrid's apertures (see Fig. 22.6), a portion of the resisting mechanism is bearing resistance against the geogrid's transverse ribs. (There is also friction resistance along the surface of the geogrid, but this is greatly product-dependent.) The stress in the transverse ribs is transferred to the longitudinal ribs, where it resists the imposed stresses, for example, at a wall facing panel. This stress must be transferred through the junctions or nodes, hence their importance.

Since bearing capacity of soil against the transverse ribs is a major resisting mechanism when using geogrids for reinforcement, this feature should be evident in anchorage or pullout tests. Figure 22.7 shows the performance of reinforcement geogrids relative to geotextiles and soil by itself. The enhanced behavior over the soil by itself and several geotextiles is readily seen. Note, however, that this behavior is for granular soils. When dealing with fine-grained silts and clays, particularly at high water contents, the response is not as beneficial.

22.3.3 Reinforcement Design with Geogrids

Since geogrids are directly competitive with geotextiles in soil reinforcement applications, the designs are essentially identical. The slope stabilization design presented earlier with geotextiles is of this type. Here the illustration will be in the form of

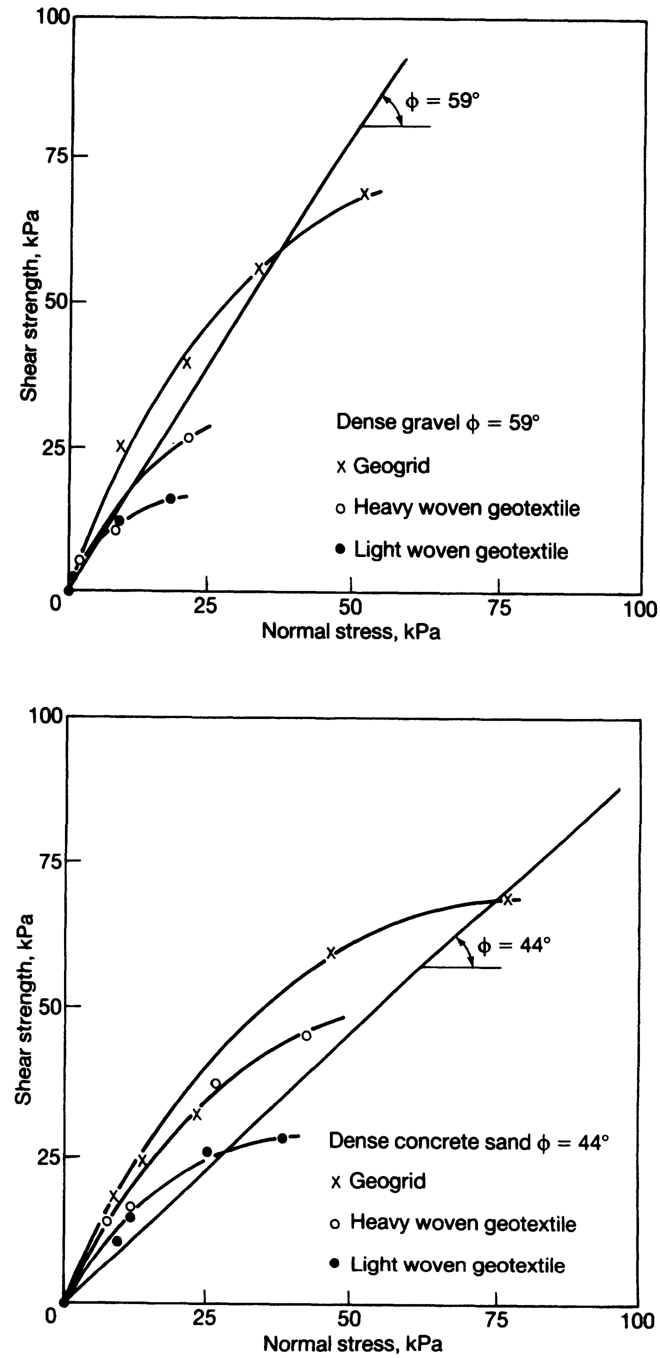
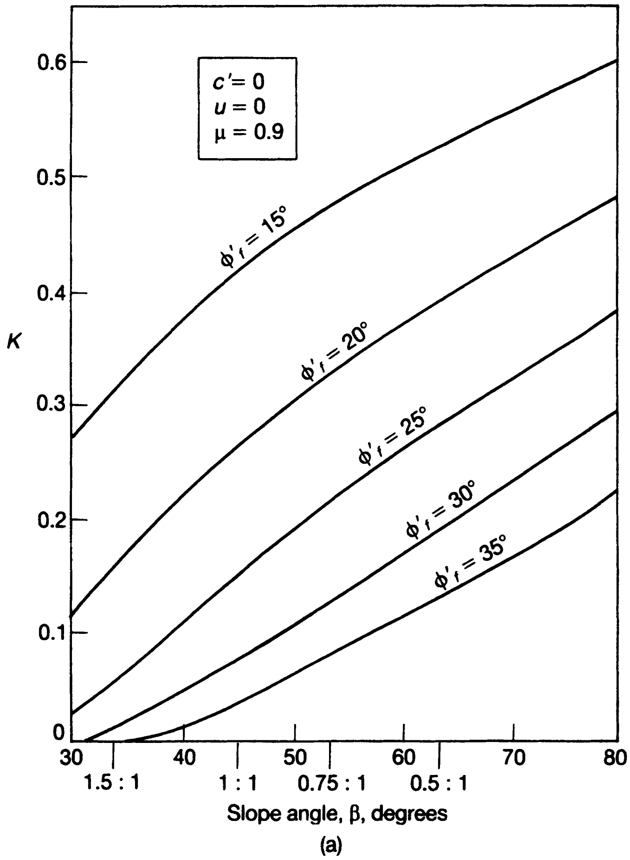


Fig. 22.7 Anchorage (pullout) behavior of geogrids vs. granular soils compared to several geotextiles.

reinforced soil for the formation of a vertical wall. The wall front can be of the wraparound style, or the geogrids can be attached to facing panels of various materials and styles. Design procedures follow along Rankine-type plastic equilibrium concepts using active earth pressure conditions for dead loads and Boussinesq concepts for live loads. The entire process is illustrated in Koerner (1990). Note that the allowable geogrid strength considering at least installation damage and creep must be included in the design. The entire process has been made simpler by use of design charts for some geogrid products. For example, Schmertmann et al. (1987) have developed a series of design charts to be used in spacing and length determination; see Figure 22.8, which is used in the following problem.



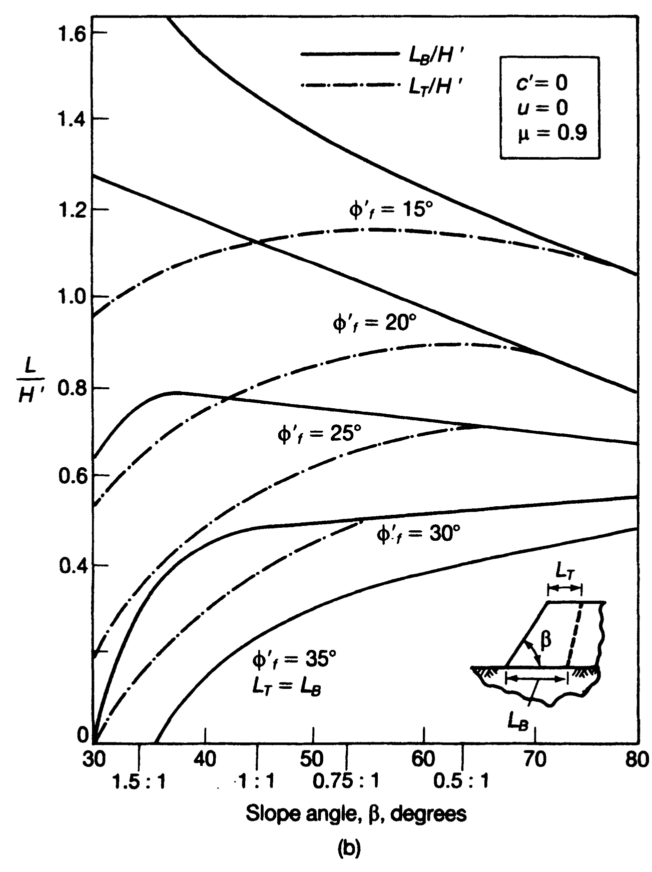


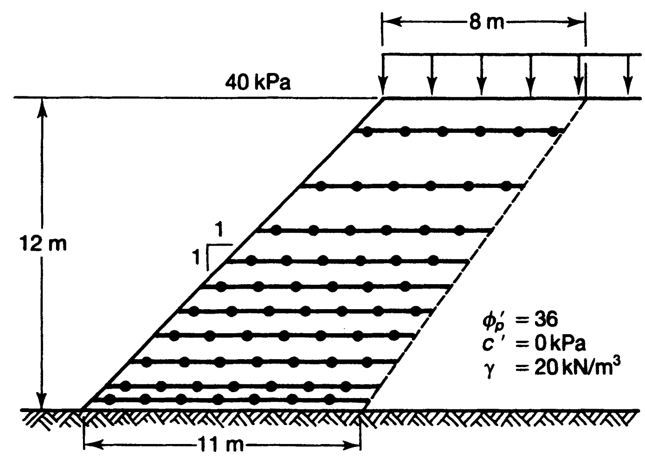
Fig. 22.8 Design guide for geogrid reinforced walls. (a) Reinforcement force coefficient. (b) Reinforcement length ratio. (*After Schmertmann et al., 1987.*)

EXAMPLE PROBLEM

Given: All assumptions valid. Required F.S. = 1.5.
Soil properties: $\phi'_p = 36°$; $c = 0$; $\gamma = 20\,\mathrm{kN/m^3}$
Slope parameters: $H = 12\,\mathrm{m}$; $\beta = 45°$; $q = 40\,\mathrm{kPa}$

Design Steps:

1. Calculated modified slope height:
   $H' = 12\,\mathrm{m} + 40\,\mathrm{kPa}/(20\,\mathrm{kN/m^3}) = 14\,\mathrm{m}$
2. Calculated factored soil friction angle:
   $\phi'_f = \tan^{-1}(\tan 36°/1.5) = 25.8°$
3. Obtain K and calculate total geogrid force:
   $K = 0.15$ (from Fig. 22.8a)
   $T = \frac{1}{2}(0.15)(20\,\mathrm{kN/m^3})(14\,\mathrm{m})^2 = 294\,\mathrm{kN/m}$
4. Select geogrid design strength and calculate number of geogrid layers:
   $\alpha_d = 30\,\mathrm{kN/m}$ (from laboratory testing)
   $N = (294\,\mathrm{kN/m})/(30\,\mathrm{kN/m}) = 9.8$; use 10 layers



5. Obtain length ratios and calculate geogrid lengths:
   $L_T/H' = 0.55$ $L_B/H' = 0.76$ (from Fig. 22.8b)
   $L_T = 0.55(14\,\mathrm{m}) = 7.7\,\mathrm{m}$; use 8 m
   $L_B = 0.76(14\,\mathrm{m}) = 10.6\,\mathrm{m}$; use 11 m
   Space geogrid layers inversely proportional to depth.

22.3.4 Other Geogrid Reinforcement Situations

Geogrids have been successfully used to support unpaved roads on very weak subgrades. Use and design parallels geotextile work and the review by Hausmann (1986) is equally applicable to geogrids as to geotextiles. Other possibilities using geogrids are also available. Since interlocking of soil, in this case stone aggregate, is possible, the idea of reinforcing the stone base course in highways and railroads has been successful. Here the effective modulus of the stone base is increased owing to the lateral confinement afforded by the geogrid. Thinner base course thicknesses or improved lifetime should result. Attempts have also been made in reinforcing asphalt pavement by sandwiching the geogrid within the structural section itself. Work by Haas (1984) has been significant in this regard and field attempts are ongoing.

22.4 GEONETS

22.4.1 Overview

Geonets are deformed or nondeformed netlike polymeric materials used in geotechnical engineering-related construction

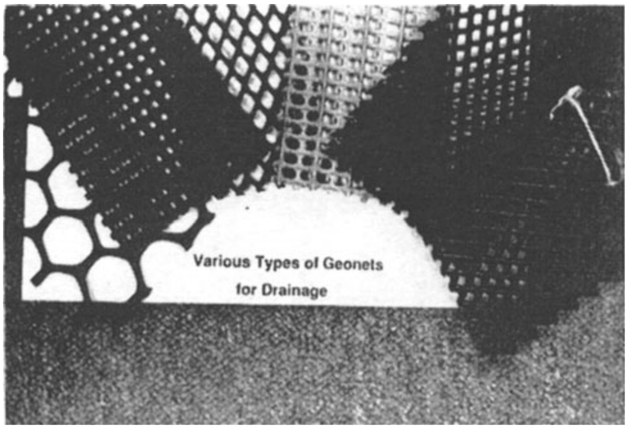


Fig. 22.9 Photographs of various types of geonets.

activities for in-plane drainage; see Figure 22.9. They are rarely, if ever, used for other functions; recall Table 22.1.

As with most geosynthetic material categories, there are a wide variety of possible manufacturing approaches used in making geonets. Perhaps the most common manufacturing technique is to extrude the molten polymer through slits in counter-rotating dies, which forms a tight net of closely spaced ribs. This net is then opened up by forcing it over a tapered mandrel until it reaches its final configurations, when it is cooled, rolled and shipped. The resulting geonet has intersecting sets of ribs at 60° to 75° apart with the crossover points being integrally bonded to one another. The ribs can be square or slightly rectangular in cross section. A number of competing products are available; see Koerner (1990). A slight variation of the above technique is to add a foaming agent to the polymer mix and then process it as just described. The foaming agent is released and forms micrometer-sized gas-filled spheres within the rib cross sections. Geonets formed in this manner can have very high ribs (resulting in increased flow capability) in comparison to the solid formed ribs. Still other variations are possible wherein a flat substrate has a built-up section of ribs superimposed on it and a completely extruded shape.

22.4.2 Properties of Geonets

Since the primary function of geonets is in-plane drainage, their flow capability in this mode is the most important property to determine. The laboratory test utilizes parallel flow on square or rectangular-shaped specimens. Obviously, the size of the test specimen must be sufficiently large to eliminate scale effects; usually 150 mm by 150 mm, or larger test specimens are used. The geonet is placed in a leakproof membrane or container and measured under a prescribed normal pressure and hydraulic gradient for its resulting flow rate; see Figure 22.10a for a solid-rib product and Figure 22.10b for a foamed-rib product.

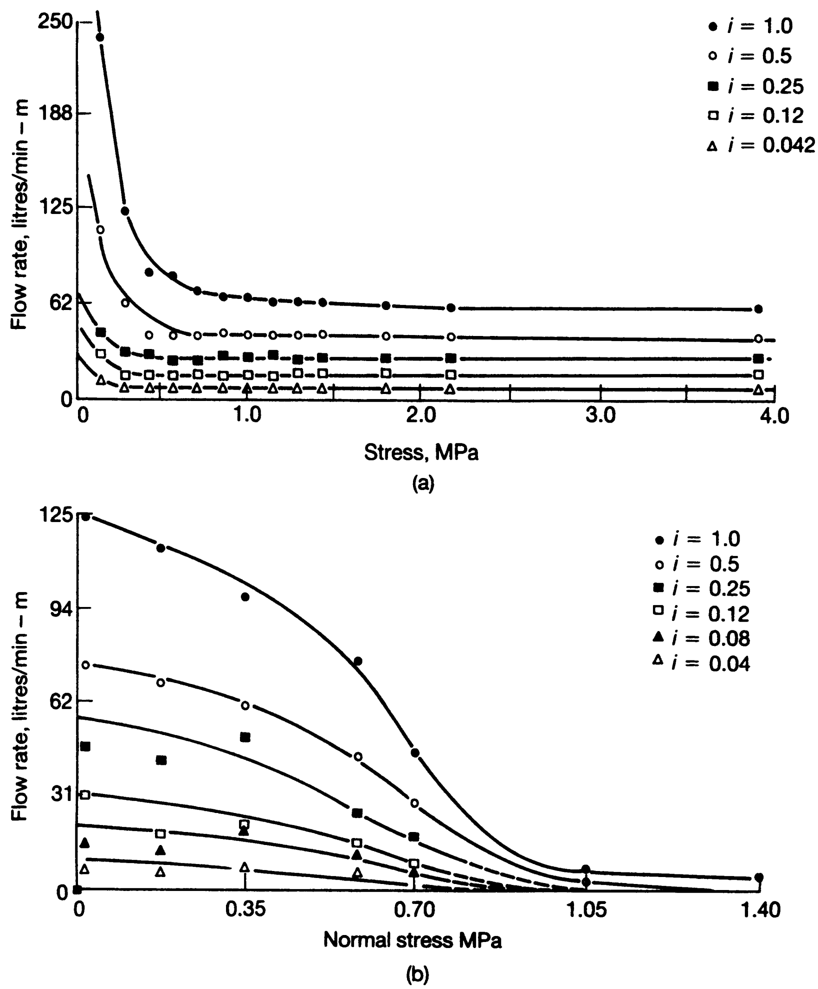


Fig. 22.10 Flow rate behavior of drainage geonets between rigid plates. (a) Flow rate behavior of solid-rib geonet (0.15 in thick). (b) Flow rate behavior of foamed-rib geonet (0.30 in thick).

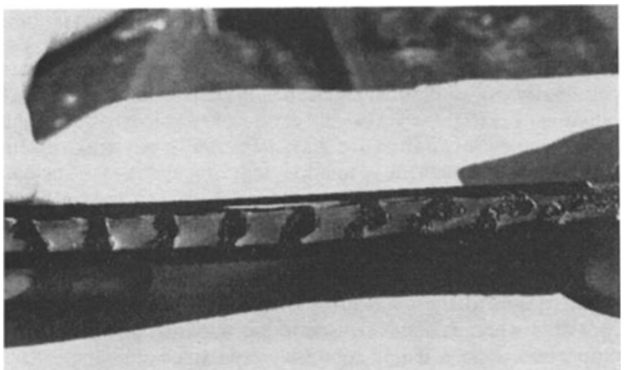


Fig. 22.11 Intrusion of adjacent materials into flow space of geonets.

It should be noted that these results are for geonets between solid plate surfaces; thus, the results represent the maximum flow that the core is capable of transmitting versus a geotextile or geomembrane on the surface that could intrude into the core space. See Figure 22.11 for this type of intrusion. Obviously, the performance test should simulate this behavior as closely as possible. Another feature about the flow curves of Figure 22.10 is that the consideration of duration of load is largely absent. According to current ASTM testing procedures (ASTM D4716), the dwell time for normal pressure application is 15 minutes and the time to take the flow measurements is also 15 minutes. For considering long-term behavior of the geonets, such testing times are usually very short. Creep of the geonet, and thereby reduction of flow rates, must generally be considered. Thus, long-duration tests are usually warranted.

22.4.3 Drainage Design Using Geonets

As with all geosynthetic design, the approach should be the formation of a factor of safety comparing the allowable property of the candidate geonet with the required, or design, value for the situation considered. With geonets, either transmissivity or flow rates can be the compared values, that is,

$$\text{F.S.} = \frac{\theta_{\text{allow}}}{\theta_{\text{req}}} \tag{22.13}$$

or

$$\text{F.S.} = \frac{q_{\text{allow}}}{q_{\text{req}}} \tag{22.14}$$

This selection is based upon consideration of whether the geonet is saturated or not. If the geonet is saturated (along with existence of laminar flow), then the transmissivity relationship can be used. If it is not saturated (or turbulent flow conditions exist), then flow rate at a specified hydraulic gradient should be used. The decision is site-specific. In either case, the flow rate value must be determined at the maximum applied normal pressure that the geonet will be subjected to.

Design must also consider creep of the geonet and intrusion of adjacent geosynthetics into the core space. Creep of the geonet itself is usually handled by having tests conducted at 2 or 3 times the maximum anticipated pressure to see whether flow is maintained. (Geonets sometimes fail by a "lay-down" of intersecting ribs against one another.) The intrusion problem is much more formidable. Not only is elastic intrusion a problem (as seen in Fig. 22.11), but also long-term creep intrusion. Note that this latter condition is out-of-plane creep of the geotextile or geomembranes into the geonet core space. Long-term tests are indeed warranted if the situation is of critical concern.

22.5 GEOMEMBRANES

22.5.1 Overview

Geomembranes are essentially impermeable sheets of polymeric materials used as liquid barriers. Known also as pond liners or flexible membrane liners, they are used to contain all types of liquids, solids, and vapors. While nothing is truly impermeable, the "equivalent permeability coefficient" of geomembranes is in the range of 10^{-11} to 10^{-14} cm/sec. This being 2 to 5 orders of magnitude lower than clay liner materials classifies them as impermeable, at least in an engineering sense. We say "equivalent permeability coefficient" to recognize that liquid does not flow through voids in a geomembrane like it does a soil. Liquid eventually passes through a geomembrane by vapor diffusion which is governed by Fick's Law of Diffusion. Furthermore, it is concentration driven rather than hydraulic gradient driven and is therefore a very slow and complicated phenomenon involving liquid/vapor/liquid phase changes. The vapor diffusion test and its calculations to arrive at an equivalent permeability coefficient is available in Koerner (1990). This discussion presumes, of course, that the geomembranes can be adequately selected, designed, installed, and maintained in such a manner that holes do not occur.

The polymers that are used to manufacture geomembranes are either thermoplastic (reversible upon repeated melting cycles), thermoset (nonreversible once cured), or combinations of both. At present, however, thermoplastic geomembranes prevail, the major types being the following:

- Polyethylene; very low-density (VLDPE), medium-density (MDPE), and high-density (HDPE)
- Polyvinyl chloride (PVC)
- Chlorinated polyethylene (CPE)
- Chlorosulfonated polyethylene (CSPE)
- Ethylene interpolymer alloy (EIA)

The manufacturing of these sheet materials follows three possible routes: extrusion, clandering, or spread-coating. These are indicated in Figure 22.12, where the term *reinforced membrane* is introduced. This reinforcement is an open woven fabric that is sandwiched within the laminated sheets of a calendered geomembrane, or as the dense nonwoven substrate when the spread-coating method is used. It (the fabric), however, does not reinforce the soil subgrade, its purpose is only to provide improved tear and impact resistance to the geomembrane and make it dimensionally stable. As with all other geosynthetics, a wide variety of geomembranes are commercially available.

22.5.2 Geomembrane Properties

Laboratory test methods for the evaluation of geomembrane properties are handled by a number of organizations, including ASTM, NSF, EPA, and Bu Rec. The specific properties are often grouped into categories of which the following are typical:

- Physical tests (specific gravity, thickness, mass per unit area, water and solvent vapor transmission)
- Mechanical tests (tensile strength, puncture resistance, impact resistance, hydrostatic resistance, friction behavior, pullout behavior)

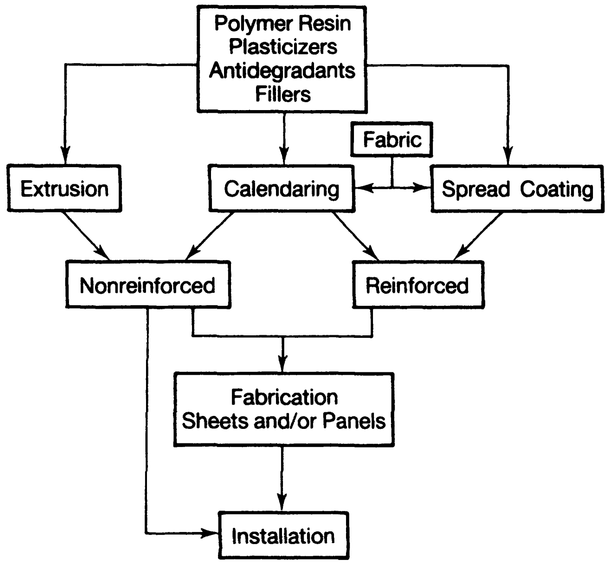


Fig. 22.12 Various manufacturing routes in formation of a geomembrane.

- Chemical tests (liquid compatibility, ozone resistance, ultraviolet resistance)
- Biological tests (microorganism compatibility)
- Endurance tests (creep behavior, abrasion resistance, soil burial resistance, durability/aging behavior)

Space precludes a complete discussion of each of the above properties, but some comments are in order on the more significant tests as far as design is concerned.

The tensile strength of a specific geomembrane is extremely important during design by function. Shown in Figure 22.13 are a series of stress-vs.-strain curves for various types of geomembranes. These curves are obtained by testing "dogbone" specimens of 6 mm width at their throat or uniform 25 mm width samples. Note that the vertical axis is not a true stress unit but rather force per unit width. In order to obtain the proper dimensions it is necessary to divide by the geomembrane thickness. Although dimensionally correct, this introduces significant inaccuracy since the thickness varies greatly during the test. While the curves of Figure 22.13 are indeed the design curves that will be used subsequently, the results (particularly the strain) might be quite different when using wide-width or out-of-plane tension tests. Work of this type is ongoing in a number of organizations.

The second test method to be discussed in some detail is the frictional behavior between geomembranes and soil. This test is modeled directly after the direct shear test common to geotechnical engineering testing. Instead of soil-to-soil friction, however, the test requires soil-to-geomembrane friction. The data of Table 22.5 was obtained in a 100-mm by 100-mm shear box with the geomembrane fixed in the lower portion of the shear box and the soil placed above it. The table lists various geomembranes to granular soils (where only friction is present) and various geomembranes to cohesive soils (where both cohesion and friction are present). Easily seen is that the frictional resistance of a specific geomembrane to a specific soil (in a specific condition) is indeed site-specific, that is, it must be individually evaluated. Also to be noted are the relatively low frictional characteristics of smooth HDPE geomembranes.

The third test method to be discussed in some detail is chemical compatibility. Indeed, all is lost if the geomembrane material is incompatible with the liquid it is meant to contain. For liquid reservoirs containing a single known liquid, the selection is not too difficult. There exists a large database of geomembrane compatibility to various liquids. These liquids include oils, sludges, chemicals, liquids of various pH values, etc. For solid waste liners, however, the situation is much more formidable. Here the waste liquid (called "leachate") is largely unknown. As a result, a worst-case scenerio of leachate selection is used. Quite often, organic solvents and phenols are selected.

Nevertheless, the leachate having been selected, geomembrane compatibility tests often are done in accordance with the EPA 9090 test procedure (U.S.E.P.A., 1984). Here candidate geomembrane test samples are incubated in the leachate for times up to 120 days. Incubation is often done at elevated temperatures. Periodically, the samples are removed, cut into test specimens and tested for tensile strength, puncture, tear, thickness, and dimensional stability. Results are graphically compared to the as-received material in terms of relative changes. While some geomembranes react to leachate and are easily identified, many do not have well-defined reactions. In such cases one must consider experimental variations and test inaccuracies that make a decision on proper selection very

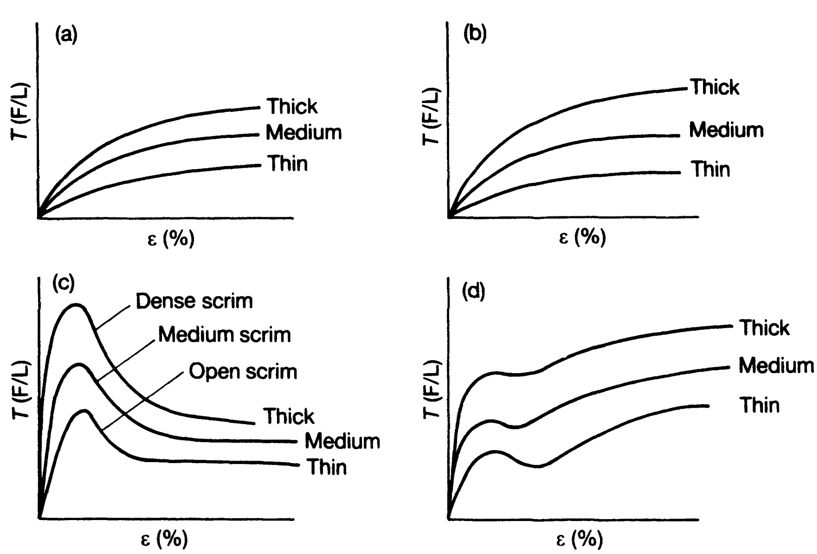


Fig. 22.13 Stress-vs.-strain response curves of various geomembranes in index tension testing. (a) PVC response curves. (b) CPE response curves. (c) CSPE-R response curves. (d) HDPE response curves.

TABLE 22.5 FRICTIONAL CHARACTERISTICS OF GEOMEMBRANES TO VARIOUS SOILS.

(a) Granular Soils (Koerner et al., 1986a)

Geomembrane	*Concrete Sand* ($\phi = 30°$)	*Ottawa Sand* ($\phi = 28°$)	*Mica Schist Sand* ($\phi = 26°$)
EPDM-R	24° (0.80)	20° (0.71)	24° (0.92)
PVC			
Rough	27° (0.90)	—	25° (0.96)
Smooth	25° (0.83)	—	21° (0.81)
CSPE-R	25° (0.83)	21° (0.75)	23° (0.88)
HDPE	18° (0.60)	18° (0.64)	17° (0.65)

(b) Cohesive Soils (Koerner et al., 1986a)

	ML-CL				*CL-ML*				*CL*			
	c	E_c(%)	ϕ(°)	E_ϕ(%)	c	E_c(%)	ϕ(°)	E_ϕ(%)	c	E_c(%)	ϕ(°)	E_ϕ(%)
Soil itself	9·0	100	38	100	12·0	100	34	100	20	100	30	100
	c_a	E_c(%)	δ(°)	E_ϕ(%)	c_a	E_c(%)	δ(°)	E_ϕ(%)	c_a	E_c(%)	δ(°)	E_ϕ(%)
Geomembrane												
PVC	8·5	94	39	100	3·7	31	23	69	14·0	70	16	53
CPE	8·0	89	40	100	3·2	27	24	71	13·0	65	16	57
EPDM-R	5·0	55	33	87	5·0	42	23	67	8·0	40	23	77
HDPE	5·0	88	26	68	2·0	17	23	67	14·0	70	15	50

difficult. Often, in the case of aggressive leachates, only HDPE (with crystallinity greater than 50 percent) is sufficiently resistant for proper geomembrane composition.

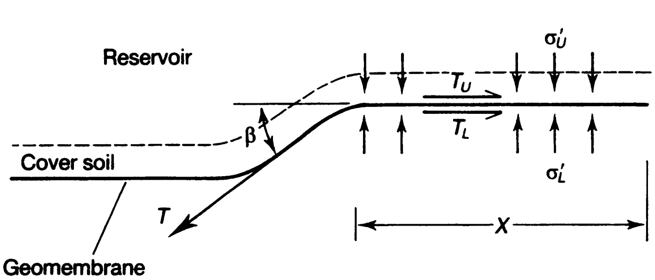
22.5.3 Liquid-Containment Liners

The design of a liquid-containment liner follows along clearly defined and sequential steps. These are as follows.

- Site selection
- Geometric layout
- Cross-section selection
- Geomembrane material selection
- Thickness design
- Side slope design
- Cover soil considerations
- Anchor trench details
- Final details and miscellaneous items

Each step in the above list uses information gained from preceding steps. Most have an analytic basis, which must be tuned to the actual situation and to its criticality.

To illustrate the situation, a thickness problem will be outlined. Note that a completely unyielding geomembrane for liquid-barrier purposes can be very thin and in the limit even a molecular thickness could suffice. Two situations prohibit this, however; one is the installation stresses, the other is localized bending. The following design is for bending, from which a thickness calculation can be made and then compared to a minimum thickness for installation survivability. Using a free body as shown below, one can take the sum of forces in a horizontal direction:



$$\Sigma F_x = 0; \qquad T\cos\beta = T_U + T_L$$

$$(\sigma_a t)\cos\beta = (\sigma'_U \tan\delta_U + \sigma'_L \tan\delta_L)X$$

$$t = \frac{(\sigma'_U \tan\delta_U + \sigma'_L \tan\delta_L)X}{\sigma_a \cos\beta} \qquad (22.15)$$

where

t = required geomembrane thickness
σ'_U = effective normal stress of cover soil (negligible in most cases)
σ'_L = effective normal stress beneath geomembrane $= \gamma H$
γ = unit weight of contained liquid
H = height (depth) of contained liquid
δ_U = friction angle of geomembrane to cover soil
δ_L = friction angle of geomembrane to subsoil
X = embankment depth to mobilize σ_a
σ_a = allowable or yield stress of geomembrane
β = subsidence angle

All values in the equation are known or can be measured with the exception of the embedment depth value X. While not a standardized test, this value can be evaluated in the laboratory. The test involves sandwiching the geomembrane between parallel plates at the desired normal stress. The anchorage depth required to mobilize the allowable or yield stress is the desired value; see GRI (1987) for the procedure and details. For the value σ_a, the curves of Figure 22.13 should be used. For well-defined breaks or yield points, as in (c) or (d), the choice is obvious. For geomembranes without a well-defined target, as in (a) and (b), one must select a maximum allowable strain, for example, 50 percent, and use the corresponding value of allowable stress.

In following other aspects of the design procedure it will be seen that cover soil stability is very troublesome. Generally, very flat side slopes are required (3 to 1 or flatter) unless special precautions such as geogrid or geotextile reinforcement are taken. Obviously, seams are very significant and these will be discussed later in the section.

TABLE 22.6 WASTE GENERATED IN U.S.A.[a].

	Millions of Tons				*Average Annual Growth (%)*	
	1977	*1988*	*1993*	*2000*	*1977–8*	*1988–93*
By type of waste						
Heavy metals	51	114	149	196	7.6	5.5
Organic chemicals	42	100	132	180	8.2	5.7
Petroleum derived	16	33	44	60	6.8	5.9
Inorganic chemicals	17	35	43	55	6.8	4.2
Other hazardous waste	5	9	13	19	5.5	7.6
Total	131	291	380	510	7.5	5.5
By method of disposal						
Landfill/surface impound	12	200	225	165	29.1	2.4
Treatment/stabilization	2	13	50	150	18.5	30.9
Incineration	neg[b]	15	35	95	—	18.5
Resource recovery	2	12	30	75	17.7	20.1
Deep-well injection	5	14	15	10	9.8	1.4
Illegal disposal	110	35	20	5	− 9.9	− 10.6
Other methods	neg[b]	2	5	10	—	20.1

[a] Hanson (1989). Source: Freedonia Group.
[b] neg = negligible.

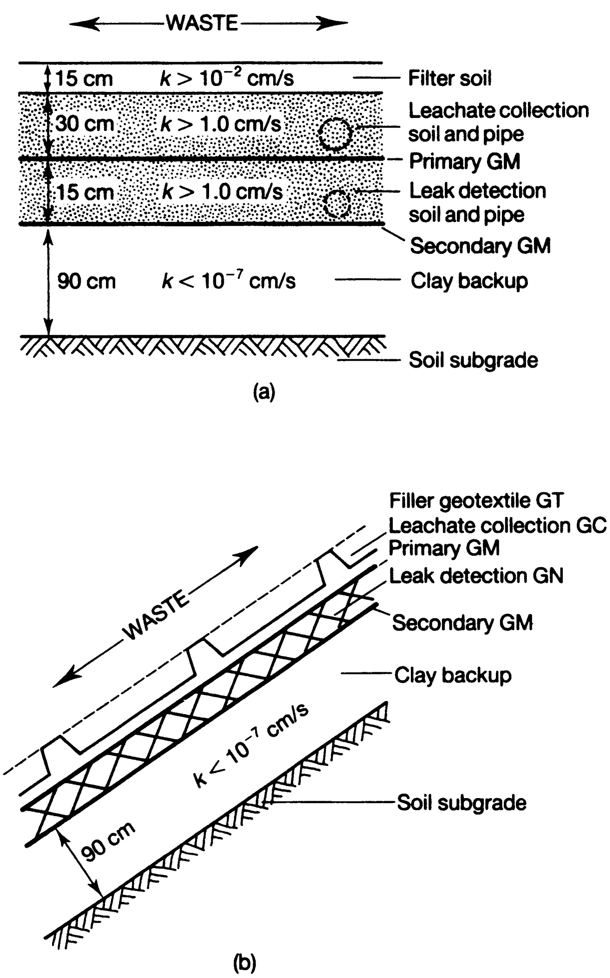


Fig. 22.14 Bottom and side liner schemes for hazardous waste disposal cells. (a) Regulated cross section. (b) Geosynthetic alternate cross section.

22.5.4 Solid-Waste-Containment Liners

Geomembranes used in the containment of solid waste pose much harsher conditions than do liquid-containment liners. This comes about owing to solids mobilizing shear stress on side slopes, the necessity of collecting and removing leachate, the necessity of providing redundancy if the primary liner leaks, and the general negative emotions that landfills of all types provoke. It should be clearly recognized that the amount of waste generated in the U.S.A. for treatment, storage and/or disposal is enormous; see Table 22.6. Clearly, the hazardous waste group is the target of most concern and, appropriately, of the most severe legislation and regulations. Because of its significance, it will be the focus of this section. Bear in mind, however, that a geomembrane design for a hazardous-waste landfill can always be modified to a less-critical situation.

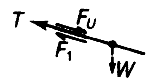
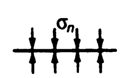
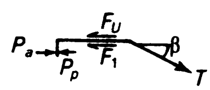
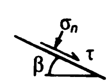
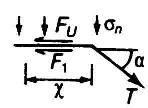
The current regulated cross section for landfills, surface impoundments, and waste piles is shown in Figure 22.14a. Considering, however, that HDPE is the liner material most often resulting from leachate immersion testing, the alternative cross section of Figure 22.14b is seeing greater use, particularly on side slopes. In the design of these systems there are many individual elements. Invariably they consist of a design model, laboratory test input, and a resulting factor of safety based upon the yield stress of the geomembrane; recall Figure 22.13d. Tables 22.7 and 22.8 summarize the design elements for the geomembrane and the drainage geosynthetics, respectively (Koerner and Richardson, 1987). Each of these models is worked out in detail with illustrative problems in an E.P.A. design manual by Richardson and Koerner (1987).

22.5.5 Other Geomembrane Applications

Other geomembrane applications, all of which can be approached on a rational design basis, are as follows (Koerner, 1990):

- Reservoir covers
- Canal liners

TABLE 22.7 VARIOUS DESIGN MODELS FOR GEOMEMBRANES IN WASTE DISPOSAL SITUATIONS[a].

Problem	Liner Stress	Free-Body Diagram	Required Properties: Geomembrane	Required Properties: Liner	Typical Factor of Safety
1. Liner self-weight	Tensile		G, t, σ_y, δ_L	β, H	10 to 100
2. Weight of filling	Tensile		$t, \sigma_y, \delta_U, \delta_L$	β, h, γ, H	0.5 to 10
3. Impact during construction	Impact		I	d, w	0.1 to 5
4. Weight of landfill	Compression		σ_y	γ, H	10 to 50
5. Puncture	Puncture		σ_p	γ, H, P, A_p	0.5 to 10
6. Anchorage	Tensile		$t, \sigma_y, \delta_U, \delta_L$	β, γ, ϕ	0.7 to 5
7. Settlement of landfill	Shear		τ, δ_U	β, γ, H	10 to 100
8. Subsidence under landfill	Tensile		$t, \sigma_y, \delta_U, \delta_L, \chi$	α, γ, H	0.3 to 10

[a] After Koerner and Richardson (1987).

Notes:

- *Geomembrane Properties*
  - G = specific gravity
  - t = thickness
  - σ_y = yield stress (or allowable stress)
  - τ = shear stress
  - I = impact resistance
  - σ_p = puncture stress
  - δ_U = friction with material above
  - δ_L = friction with material below
  - χ = mobilization distance
- *Landfill Properties*
  - β = slope angle
  - H = height
  - γ = unit weight
  - h = lift height
  - α = subsidence angle
  - ϕ = friction angle
  - d = drop height
  - W = weight
  - p = puncture force
  - A_p = puncture area

TABLE 22.8 VARIOUS DESIGN CONSIDERATIONS FOR DRAINAGE GEOCOMPOSITES IN WASTE DISPOSAL SITUATIONS[a].

Problem	Reason	Approach	Required Properties: Geocomposite	Required Properties: Landfill	Severity of Problem
1. Strength of core	Avoid crushing	F.S. = $\sigma_{ult}/\sigma_{max}$	σ_{ult}	γ, H	Minor
2. Flow in core	First approximation	F.S. = $\theta_{allow}/\theta_{act}$	θ_{allow}	$\gamma, H, i, q_{act}, \theta_{act}$	Minor
3. Creep of core	First reduction	F.S. = $\theta'_{allow}/\theta_{act}$	θ'_{allow}	$\gamma, H, q_{act}, \theta_{act}$	Nil to major
4a. Elastic intrusion of geomembrane	Second reduction	Elastic plate theory	E, μ, x, y	$\gamma, H, q_{act}, \theta_{act}$	Major
4b. Elastic intrusion of geotextile	Second reduction	Elastic plate theory	E, μ, x, y	$\gamma, H, q_{act}, \theta_{act}$	Major
5a. Creep intrusion of geomembrane	Third reduction	Creep theory	$\dot{\varepsilon}(\sigma, t), x, y$	γ, H, t	Unknown
5b. Creep intrusion of geotextile	Third reduction	Creep theory	$\dot{\varepsilon}(\sigma, t), x, y$	γ, H, t	Unknown

[a] After Koerner and Richardson (1987).

Notes:

- *Geocomposite Properties*
  - σ_{ult} = ultimate compression strength
  - σ_{max} = maximum stress
  - σ = applied stress
  - θ_{allow} = transmissivity
  - t = time
  - E = modulus of elasticity
  - μ = Poisson's ratio
  - x, y = core dimensions
  - $\dot{\varepsilon}(\sigma, t)$ = strain rate
- *Landfill Properties*
  - γ = unit weight
  - H = height
  - i = hydraulic gradient
  - q_{act} = actual (design) flow rate
  - θ_{act} = actual (design) transmissivity
  - t = time

TABLE 22.9 TYPES OF GEOMEMBRANE SEAMING METHODS[a].

(a) Adhesive and Tapes

Base Polymer of Common Geomembrane Systems	*Solvent*		*Bodied Solvent*		*Solvent Adhesive*		*Contact Adhesive*		*Vulcanizing tape/Adhesive*		*Tape,*
	M[b]	*F[b]*	*M*	*F*	*M*	*F*	*M*	*F*	*M*	*F*	*F*
Thermoplastics											
Polyvinyl chloride (PVC)	X	X			X	X	X	X			X
Nitrile-PVC (TN-PVC)	X	X			X	X	X	X			X
Ethylene interpolymer alloy (EIA)											
Crystalline thermoplastics											
Low-density polyethylene (LDPE)							X	X			X
High-density polyethylene (HDPE)							X	X			X
Elastomers											
Butyl rubber (IIR)							X	X	X	X	
Ethylene propylene diene monomer (EPDM)							X	X			X
Neoprene (polychloroprene)							X	X			
Epichlorohydrin rubber (CO)							X	X			
Thermoplastic elastomers											
Chlorinated polyethylene (CPE)	X	X	X	X	X	X	X	X			X
Hypalon (chlorosulfonated polyethylene) (CSPE)	X	X	X	X	X	X	X	X			X
Thermoplastic EPDM (T-EPDM)							X	X			

(b) Thermal and Mechanical

Base Polymer of Common Geomembrane Systems	*Thermal methods*					*Extrusion (Fusion) Welding,*	*Mechanical,*
	Hot Air		*Hot Wedge*		*Dielectric,*		
	M	*F*	*M*	*F*	*M*	*F*	*F*
Thermoplastics							
Polyvinyl chloride (PVC)	X	X			X		X
Nitrile-PVC (TN-PVC)	X	X			X		X
Ethylene interpolymer alloy (EIA)	X	X					
Crystalline thermoplastics							
Low-density polyethylene (LDPE)	X	X	X	X			X
High-density polyethylene (HDPE)		X	X	X		X	X
Elastomers							
Butyl rubber (IIR)							
Ethylene propylene diene monomer (EPDM)							
Neoprene (polychloroprene)							
Epichlorohydrin rubber (CO)							
Thermoplastic elastomers							
Chlorinated polyethylene (CPE)	X	X			X		
Hypalon (chlorosulfonated polyethylene) (CSPE)	X	X			X		
Thermoplastic EPDM (T-EPDM)	X	X					

[a] After Frobel (1984).

[b] M, manufactured or factory seams; F, field fabrication.

TABLE 22.10 OVERVIEW AND CRITIQUE OF NONDESTRUCTIVE GEOMEMBRANE SEAM TESTS[a].

	Primary User			General Comments					
Nondestructive Test Method	*Contractor*	*Design Engr. Insp.*	*Third Party Insp.*	*Cost of Equipment, $*	*Speed of Tests*	*Cost of Tests*	*Type of Result*	*Recording Method*	*Operator Dependency*
1. Air lance	Yes	n/a	n/a	$200	Fast	Nil	Yes–No	Manual	Very high
2. Mechanical point (pick) stress	Yes	n/a	n/a	Nil	Fast	Nil	Yes–No	Manual	Very high
3. Vacuum chamber (negative pressure)	Yes	Yes	n/a	$1000	Slow	V. high	Yes–No	Manual	High
4. Dual seam (positive pressure)	Yes	Yes	n/a	$200	Fast	Mod.	Yes–No	Manual	Low
5. Ultrasonic pulse echo	n/a	Yes	yes	$5000	Moderate	High	Yes–No	Automatic	Moderate
6. Ultrasonic impedance	n/a	Yes	yes	$7000	Moderate	High	Qualitative	Automatic	Unknown
7. Ultrasonic shadow	n/a	Yes	yes	$5000	Moderate	High	Qualitative	Automatic	Low

[a] After Koerner and Richardson (1987).

- Caps and closures of landfills
- Earth dam retrofit liners
- Concrete dam retrofit liners
- Vertical cutoff barriers
- Secondary underground storage tank liners
- Ground vapor barriers (against moisture, methane, radon, etc.)
- Heap leaching pads in the mining industry
- Thermal extraction from salt ponds

22.5.6 Geomembrane Details

Details are important in the construction of any system, but nowhere are they more important than in geomembrane systems. One leak can defeat the purpose of the entire liner system. Thus, worksmanship takes on an extremely high priority. Even third-party construction quality assurance (CQA) consulting is required on many installations. While every location of the liner is a potential problem, the field seams are rightfully the focus of most attention. The seaming methods are related to the type of polymer; see Table 22.9 for an overview (Frobel, 1984).

Regarding inspection of the seams, the choices are between destructive and nondestructive testing. Destructive tests require the cutting of a coupon from the geomembrane and then testing it in shear or in peel (tension). Such tests are good indicators of the manner and technique of seaming, but do require patching and tell nothing of the continuity between individual tests. Thus, the need for nondestructive tests, of which there are many; see Table 22.10. These methods are elaborated upon in various references. Of them, the air-lance and pick tests are really contractors' methods for investigating missed seam areas. Current specifications often call for vacuum-box testing, but when required for 100 percent of the seams this is very time-consuming, tedious, boring, and costly. Future trends may be toward the ultrasonic techniques and, in particular, the ultrasonic shadow method (Lord et al., 1986; Koerner et al., 1987).

Details around pipes, connections, and fittings are very difficult to design and construct. As much as possible, modulus mismatches should be kept to a minimum; that is, a liner should not be anchored firmly to steel or concrete. Batten strips, rounded or tapered corners, slack zones, etc., must all be considered in the design of such details. Most manufacturers have excellent experience in this regard and their promotional literature has a wealth of good information.

In the final analysis, however, it is the field installation contractor who holds the key to a successful and trouble-free project. Experience, workmanship, and attention to detail cannot be overemphasized.

22.6 GEOCOMPOSITES

22.6.1 Overview

The relatively ill-defined area called geocomposites consists of manufactured products using combinations of geotextiles, geogrids, geonets, and/or geomembranes in laminated or composite form. Generally, but certainly not always, the end-product is completely polymeric. Other options include using fiberglass or steel for tensile reinforcement, sand in compression or as a filler, dried clay for subsequent expansion as a liner, or bitumen as a waterproofing agent. Since a geocomposite can be made for any specific function (recall Table 22.1) this section will be subdivided to include all of the primary geosynthetic functions. Owing to the widespread use of drainage geocomposites, however, this particular area will be emphasized.

22.6.2 Geocomposites in Separation

Many erosion control systems are being made from a continuous mat of polymer (nylon and PVC have been used successfully) held together with an open geotextile substrate. Drainage ditches and swales used to intercept runoff in highway and railroad soil slopes regularly use such systems in place of concrete ditches. By using a geosynthetic, a number of advantages are gained:

- Conformability to irregular surfaces
- Flexibility for subsequent soil subgrade movements
- Promotion of vegetative growth, and thus good asthetics
- Low runoff velocities
- Elimination of need for downstream energy dissipation
- Significantly lower expense than concrete or rip-rap

Many State DOTs are specifying and using such systems. While exposed to ultraviolet degradation, the systems appear to have lifetimes adequate for their use. Vegetative growth is certainly helpful in this regard.

22.6.3 Geocomposites in Reinforcement

Many attempts at increasing the tensile properties of modulus and strength and/or decreasing creep by using materials with strength greater than polymers have been tried. Steel stands have been used effectively to make heavy filter mattresses laid directly on the seafloor to support concrete piers. Fiberglass has been used by a number of companies, which is usually woven or knitted in continuous filaments for enhanced strength properties. Both of these materials (steel and fiberglass) have drawbacks of long-term corrosion that must be contemplated in the design.

Quite a different approach is to use continuous-filament polymer yarn along with soil to form reinforced slopes. The technique uses a soil spray with many fibers included in it to actually construct the entire slope (Leflaive, 1986). Almost-vertical slopes that support relatively large surcharge loads have been constructed.

A number of specific polymers have been used in conjunction with one another with excellent results. One of these types uses high-tenacity polyester yarns that are grouped together and held in a polypropylene sheath to form rods, strips, grids, links, and webs (Koerner, 1986b). Another approach has used polyester yarn in the warp direction and polypropylene yarn in the fill direction to make anisotropic high-strength fabrics. The possibilities are enormous and the geosynthetic manufacturing industry appears ready to develop new products as the demand warrants.

22.6.4 Geocomposites in Filtration

The most outstanding example of a geocomposite filter is the Dutch soil–geotextile filter mattress (Visser and Mouw, 1982). Here a composite is formed consisting of the following layers from bottom to top:

- High-strength steel-reinforced geotextile
- 110 mm of sand
- Geotextile separator
- 110 mm of sandy gravel
- Geotextile separator
- 140 mm of gravel
- Geotextile upper layer

The system was made into 200-m long by 42-m wide mattresses and placed on the ocean floor to support concrete piers for a storm surge barrier. The Eastern Scheldt River Barrier is probably the most significant project incorporating geosynthetics to date, particularly considering that the envisioned lifetime is 200 years (Visser and Mouw, 1982).

The use of two geotextile filters needled together, each designed for the particular soil placed adjacent to them, has seen common use and has been quite successful. Other options are also available.

22.6.5 Geocomposites in Drainage

This area is perhaps the fastest-moving of all of the geocomposite options available to the user. It can be subdivided into three topics, since each area is very application-specific.

"Sheet drains" consist of rolls or panels of drainage cores protected by a geotextile filter on one side (to allow for liquid to enter) and a geotextile, geomembrane, or structure on the other side; see Figure 22.15a. The cores vary greatly in their polymer type, shape, and configuration. This being the case, it should come as no surprise that the flow rate capability should vary greatly as well (Koerner et al., 1986a). The test for evaluating these products is identical to that described in the geonet section—recall Section 22.4. It should be noted that geonets protected as described above are indeed geocomposites and all of the details described there, namely, intrusion, creep, etc., apply here as well. At least two features distinguish geocomposite drains from geonets; first, geocomposite drains usually have greater flow rate capability and, second, they usually have a pronounced collapse strength. Figure 22.16 illustrates these points for selected products, where the sensitivity to normal stress and hydraulic gradient is evident. Thus, each product must have this type of information available for design purposes.

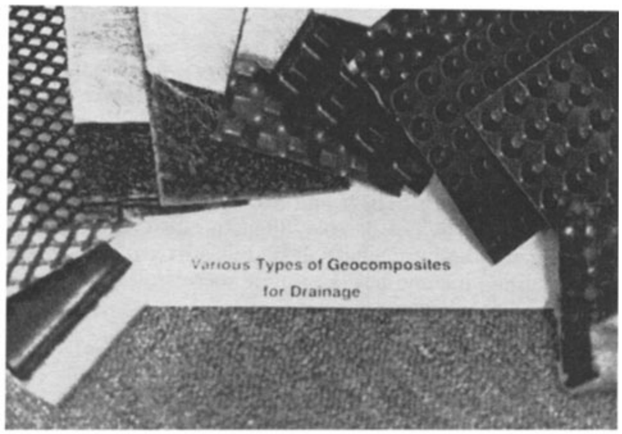
Regarding the design (or required) flow-rate values for use in a factor-of-safety calculation, the intended application is most significant. Some applications (in approximate order of increasing flow-rate demand) are:

- Fine-grained soil drainage
- Roof-garden drainage
- Plaza-deck drainage
- Sport-field drainage
- Capillary breaks
- Seeping-slope drainage (soil or rock)
- Leachate collection systems
- Surface-water drains
- Retaining-wall drains

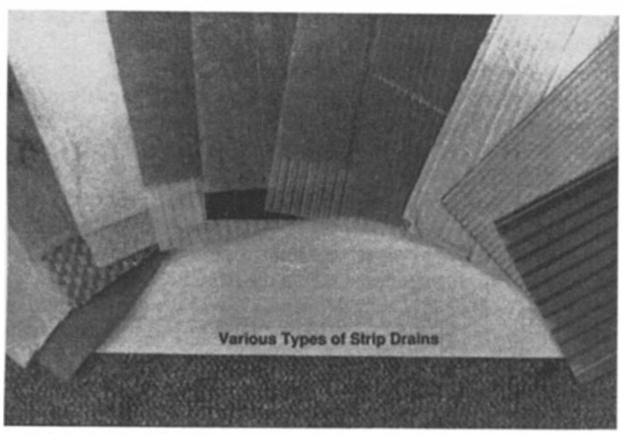
The actual calculation of required flow-rate capability is obtained by appropriate theory, such as Darcy's formula, flow nets, empirical guides and charts, etc. (Koerner et al., 1986b).

A final comment on sheet-drain specifications is in order, since the products available differ so widely in their performance. There is no "or equal" in this area. A proper specification should require a specified flow rate, at a given normal stress, at a given hydraulic gradient. If desirable, further details as to normal stress dwell time, soil adjacent to the candidate product, etc., can also be included.

"Strip drains" (or prefabricated vertical drains, also incorrectly called wick drains) are used to rapidly consolidate fine-grained saturated soil. They are true drainage geocomposites, consisting of a drainage core completely surrounded by a geotextile filter; see Figure 22.15b. As with sheet drains,

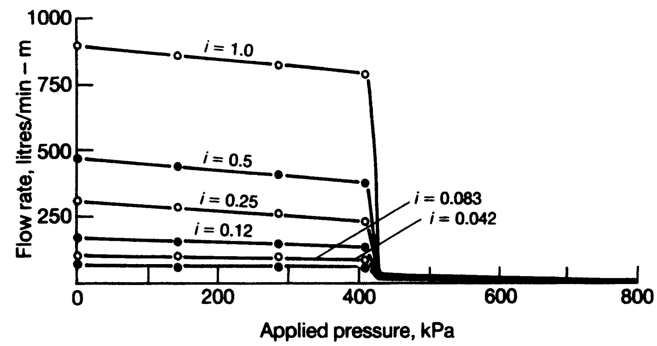


(a)

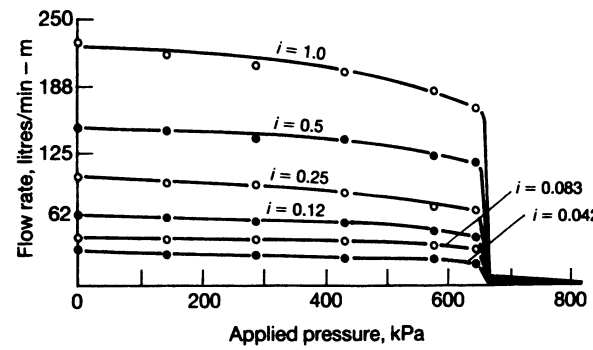


(b)

Fig. 22.15 Photographs of geocomposite drainage systems. (a) Various types of sheet drains. (b) Various types of strip drains (prefabricated vertical drains).



(a)



(b)

Fig. 22.16 Flow rate capability for selected geocomposite drainage systems. (a) Flow rate behavior of product *a*. (b) Flow rate behavior of product *b*.

there are many competing styles of strip drains currently available. Their design can be based on volumetric flow rate considerations, but sufficient analytic work has been done such that an equation for time for consolidation is currently available (Hansbo, 1979):

$$t = \frac{D^2}{8c_h}\left(\ln\frac{D}{d} - 0.75\right)\left(1 - \frac{1}{\bar{U}}\right) \tag{22.16}$$

where

t = time for U percent consolidation
$\bar{U}$ = consolidation expressed as a ratio
c_h = horizontal (radial) coefficient of consolidation
D = strip drain spacing (for triangular pattern use 1.05 spacing; for rectangular pattern use 1.13 spacing)
d = equivalent diameter of strip drain ($\simeq$ circumference/π)

A completely worked example with a design chart using this formula is available in Koerner (1990). Further modifications and a comprehensive review of the subject are available in Kraemer and Smith (1986).

One point of concern, however, that should be considered in designing strip drains is their flexibility. Since the axial shortening of strip drains during consolidation of the surrounding soil could be 20 to 30 percent of their original installed length, one must ask how this shortening is accomplished. If a very localized area is affected (as one would expect, since soils are invariably nonhomogeneous), the stiff drains could kink, thereby stopping flow. Thus, strip drains should be categorized as stiff, intermediate, or flexible and viewed in light of their anticipated shortening. A laboratory test to evaluate this phenomenon is available (Suits et al., 1985, 1987).

Lastly, it is interesting to consider what a large number of strip drains penetrating through a weak soil stratum would contribute toward soil stability. Since soft soil foundation failures as surcharge is increased are common in rapid consolidation projects, the strip drains could indeed provide a reinforcing effect to the site. Typically, the tensile strength of strip drains is 1 to 2 kN per drain. Analysis is ongoing in this area as well as others involving use of strip drains.

"Edge drains" have recently emerged as geocomposite drains in their own right. Originated in 1985 there are today from 10 to 15 competing products. They are generally 300 or 450 mm high, from 25 to 37 mm thick and hundreds of meters long. They are installed in a vertical position immediately adjacent to the edge of a highway pavement for the purpose of subsurface drainage. At spacings of 100 and 200 m they are intercepted and the drainage is diverted to a ditch or swale away from the pavement area.

Both design and testing of highway edge drains are still in a formative stage but are being actively pursued by a number of organizations (see Koerner, 1990, for some of these details).

22.6.6 Geocomposites as Moisture Barriers

Various combinations of geosynthetics, along with asphalt, clay, elastomers, etc., can be combined to make effective moisture barriers. The spread-coating method described in Figure 22.12 is of this type. Many more complex situations are also available. Some of the larger types have asphalt layers within geotextiles that are rolled onto a site and have heat-sealing for their seaming technique. Dry bentonite clay has been effectively sandwiched between geotextiles, placed, and moistened allowing the clay to swell, thereby forming the required barrier. Fiberglass fabric has been used between bitumen sheets for preventing crack reflection in highway repairs. The list of possibilities is essentially endless.

This last comment is perhaps fitting to close this chapter on geosynthetics. Indeed, the entire area is new, exciting, and full of possibilities to effectively solve a wide range of geotechnical engineering-related problems.

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