Part I

General issues

1

The design principles of geosynthetics

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1.1   Introduction

As with all new materials design, one adopts and adapts earlier approaches from other and/or similar materials. With geosynthetic materials design, the closest allied fields are construction materials and, in particular, soil materials as encompassed within the discipline of geotechnical engineering. As is to be expected with the gradual maturing of the geosynthetic area, the design methods have advanced from very simplistic to quite detailed and still emerging.

In this regard, the chapter will describe the following:

1 'Design by cost' (exemplifying past practice).
2 'Design by specification' *and* 'Design by function' (exemplifying present practice).
3 'Design using probability' *and* 'Load and reduction factor design' (exemplifying possible future practice).

1.2   Past practice in geosynthetic design

Manufacturers' specifications appeared almost simultaneously with the development and introduction of each geosynthetic product's entry into a particular application. Geotextile and geomembrane manufacturers led the way with product specifications accompanying each product throughout the 1960s and 1970s. The downside of such specifications was that, either overtly or by using subtle test methods, the net result was to use that particular product, thereby excluding all others. Of course, the designer was at liberty to 'cut and paste', thereby forming a project-specific specification but this was difficult owing to rapid changes in the emerging technology and the general lack of field performance and designers experience. Thus, which tests to include, which minimum or maximum values to select, which test procedures to evoke and which testing frequencies to require were all very subjective issues. As a result, the method often used by the designer could be described as 'design by cost'.

Design by cost is quite simple. The funds available are divided by the area to be covered, and a maximum available unit price that can be allocated for the geosynthetic product is calculated. The geosynthetic product with the best properties for the site-specific application is then selected within this unit price limit and according to its availability. The method is obviously weak technically but is one that has been practised and very often resulted in adequate performance. It perhaps typified the situation in the early days of geosynthetics, but it is very outmoded by the current standard of practice.

1.3   Present practice in geosynthetic design

A defining point in geosynthetics was the first international conference on the subject in Paris in 1977. This conference spurred the first books on the topic (Koerner and Welsh, 1980; Rankilor, 1981) both of which collected more advanced and generic specifications and laid the groundwork for designing by function. Thus, from 1980 to the present, geosynthetic design has taken two parallel routes, 'design by specification', and 'design by function'. In general, design by specification is used for ordinary and non-critical applications, while design by function is used for site-specific and generally critical applications. Each will be explained.

1.3.1   Design by specification

Design by specification is very common and is used extensively when dealing with public agencies and many private owners as well. In this method, several application categories are listed in association with various physical, mechanical, hydraulic and/or endurance properties. The application areas are usually related to the intended primary function.

A federal agency that has formulated a unified approach in the USA for geotextiles is the American Association of State Highway and Transportation Officials (AASHTO). In its M288 geotextile specifications, AASHTO provides for three different strength classifications (Table 1.1). The classifications are essentially a list of minimum strength properties meant to withstand varying degrees of installation survivability stresses. It is the first step in the process.

- Class 1. For severe or harsh survivability conditions where there is a greater potential for geosynthetic damage.
- Class 2. For typical survivability conditions; this is the default classification to be used in the absence of site-specific information.
- Class 3. For mild survivability conditions where there is little or no potential for geosynthetic damage.

The second step is to select one of several different tables according to the specific function. These functions follow the intended application. They are filtration,

Table 1.1 AASHTO M288 geotextile strength property requirements

	Test method	Units	Geotextile Classification[a]					
			Class 1		Class 2		Class 3	
			Elongation <50%[b]	Elongation >50%[b]	Elongation <50%[b]	Elongation >50%[b]	Elongation <50%[b]	Elongation >50%[b]
Grab strength	ASTM D4632	N	1400	900	1100	700	800	500
Sewn seam strength[c]	ASTM D4632	N	1200	810	990	630	720	450
Tear strength	ASTM D4533	N	500	350	400[d]	250	300	180
Puncture strength[e]	ASTM D4833	N	500	350	400	250	300	180
Burst strength[f]	ASTM D3786	kPa	3500	1700	2700	1300	2100	950
Permittivity	ASTM D4491	s^{-1}	Minimum property requirements for permittivity, apparent opening size and ultraviolet stability are based on geotextile application. Refer to separate tables for subsurface filtration, separation, stabilization or permanent erosion control					
Apparent opening size	ASTM D4751	mm						
Ultraviolet stability	ASTMD4355	%						

[a]Required geotextile classification is designated in accompanying tables for the indicated application. The severity of installation conditions for the application generally dictate the required geotextile class. Class 1 is specified for more severe or harsh installation conditions where there is a greater potential for geotextile damage, and Class 2 and Class 3 are specified for less severe conditions.
[b]As measured in accordance with ASTM D4632. Note that woven geotextiles fail at elongations (strains) less than 50%, while non-woven geotextiles fail at elongation (strains) greater than 50%.
[c]When sewn seams are required. Overlap seam requirements are application specific.
[d]The required MARV tear strength for woven monofilament geotextiles is 250 N.
[e]Puncture strength will probably change from ASTM D4833 to ASTM D6241 with higher values.
[f]Burst strength will probably be omitted in the near future.

Table 1.2 AASHTO M288 subsurface filtration (called 'drainage' in the actual specification) geotextile requirements

Property	Test method	Units	Requirements for the following amounts of *in situ* soil passing 0.075 mm[a]		
			<15%	15–50%	>50%
Geotextile class			Class 2 from Table 1.1[b]		
Permittivity[c,d]	ASTM D4491	s⁻¹	0.5	0.2	0.1
Apparent opening size[c,d]	ASTM D4751	mm	0.43 maximum average roll value	0.25 maximum average roll value	0.22 maximum average roll value
Ultraviolet stability (retained strength)	ASTM D4355	%	50% after exposure for 500 h		

[a]Based on the grain size analysis of *in situ* soil in accordance with AASHTO T88.
[b]Default geotextile selection. The engineer may specify a Class 3 geotextile from Table 1.1 for trench drain applications based on one or more of the following.
 1. The engineer has found Class 3 geotextiles to have sufficient survivability based on field experience.
 2.The engineer has found Class 3 geotextiles to have sufficient survivability based on laboratory testing and visual inspection of a geotextile sample removed from a field test section constructed under anticipated field conditions.
 3. The subsurface drain depth is less than 2 m, the drain aggregate diameter is less than 30 mm and the compaction requirement is equal to or less than 95% of the value AASHTO specified in T99.
[c]These default filtration property values are based on the predominant particle sizes of the *in situ* soil. In addition to the default permittivity value, the engineer may require geotextile permeability and/or performance testing based on engineering design for drainage systems in problematic soil environments.
[d]Site-specific geotextile design should be performed especially if one or more of the following problematic soil environments are encountered: unstable or highly erodable soils such as non-cohesive silts; gap-graded soils; alternating sand–silt laminated soils; dispersive clays; rock flour.
[e]For cohesive soils with a plasticity index greater than 7, the geotextile maximum average roll value for the apparent opening size is 0.30 mm.

separation, stabilization, erosion control, temporary silt fences and prevention of reflective cracking. Table 1.2 presents the appropriate table for filtration applications. See Koerner (2005b) for the remaining tables and a more complete description together with example problems. It should be mentioned that many federal agencies worldwide have similar generic specifications.
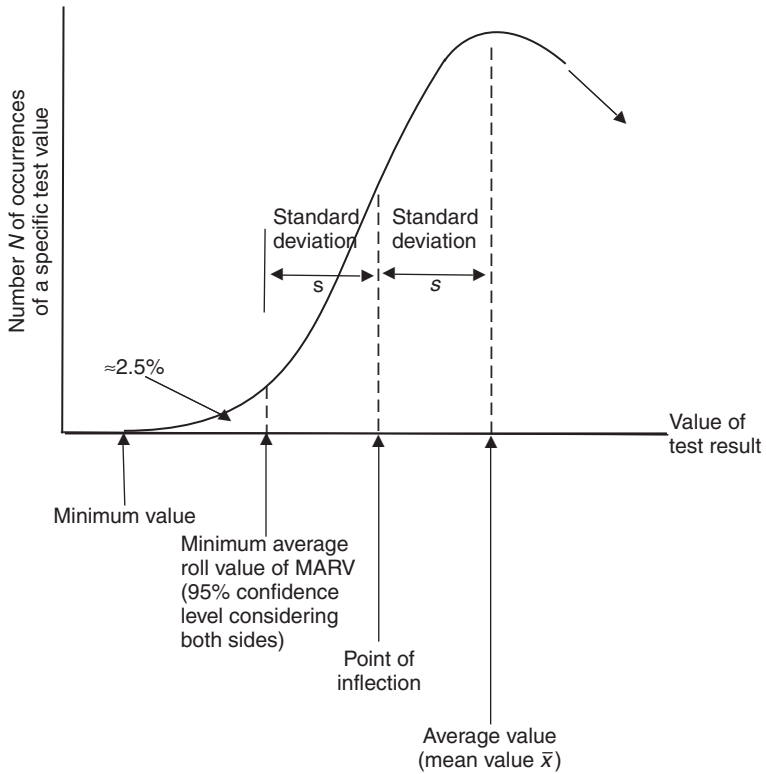
 There are additional non-federal and non-proprietary specifications that have been developed throughout the 1990s up to the present, most notable among which

are the generic specifications of the Geosynthetic Research Institute (GRI). At present, they are as follows.

GRI-GCL3   *Test Methods, Required Properties, and Testing Frequencies of Geosynthetic Clay Liners (GCLs).*

GRI-GM13   *Test Properties, Required Properties, and Testing Frequency and Recommended Warranty for High Density Polyethylene (HDPE) Smooth and Textured Geomembranes.*

GRI-GM17   *Test Properties, Required Properties, and Testing Frequency and Recommended Warranty for Linear Low Density Polyethylene (LLDPE) Smooth and Textured Geomembranes.*

GRI-GM18   *Test Properties, Required Properties, and Testing Frequency and Recommended Warranty for Flexible Polypropylene (fPP and fPP-R) Nonreinforced and Reinforced Geomembranes.* This has been temporarily suspended pending additional testing.

GRI-GM19   *Seam Strength and Related Properties of Thermally Bonded Polyolefin Geomembranes.*

GRI-GM21   *Test Methods, Required Properties, and Testing Frequency and Recommended Warranty for Ethylene Propylene Diene Terpolymer (EPDM) Nonreinforced and Scrim Reinforced Geomembranes.*

GRI-GT10   *Test Methods, Properties and Frequencies for High Strength Geotextile Tubes used as Coastal and Riverine Structures.*

GRI-GT12   *Test Methods and Properties for Nonwoven Geotextiles Used as Protection (or Cushioning) Materials.*

GRI-GT13   *Test Methods and Properties for Geotextiles Used as Separation Between Subgrade Soil and Aggregate.*

All these specifications are available free on the Geosynthetic Institute's web site at http:/www.geosynthetic-institute.org. There are others available by different groups, but this gives a sampling of generic specifications in the geosynthetics industry.

It must be cautioned that, when using a design-by-specification method, the specifications sometimes list *minimum* required properties, whereas some manufacturers' literature may list either *average lot* or *minimum average roll* property values. By comparing such a specification value with the manufacturer's listed values, one may be comparing different sets of numbers. This is because average lot value is the mean value for the particular property in question from all the tests made on that lot of material. This may be the compilation of thousands of tests made over many months or even years of production of that particular product style. Thus, the average lot value is considerably higher than the minimum value (Fig. 1.1). An intermediate value between these two extremes is the minimum average roll value (MARV). The MARV is the average of a representative number of tests made on selected rolls of the lot in question, which is limited in area to the particular site in question. This value is numerically equivalent to two standard

Standard
deviation

Standard
deviation

s

s

≈2.5%

Value of
test result

Minimum value

Minimum average
roll value of MARV
(95% confidence
level considering
both sides)

Point of
inflection

Average value
(mean value $\bar{x}$)

Number N of occurrences
of a specific test value

1.1 Relative relationships of different statistical values used in
geosynthetic specifications and manufacturers' literature.

deviations lower than the mean, or average, lot value. Thus, it is seen that the
MARV is the minimum of a limited series of average roll values. These different
values are shown schematically in Fig. 1.1.

Clearly, the design-by-specification method must compare like sets of numbers.
If the intent of the specification is to list MARVs (as it is with Tables 1.1 and 1.2),
then the manufacturer's listed mean or average values must be decreased by two
standard deviations (approximately 5–20%) if average lot values are given. Only
if MARVs are given by the manufacturer can they be directly compared with a
MARV-based specification value on a like-set-of-number basis.

It is important to note that only in geotextile design do we use the concepts of
MARV and (also the maximum coverage roll value) (MaxARV). This is due to the
greater statistical variation in geotextile properties versus other geosynthetics.

1.3.2   Design by function

Design by function consists of assessing the primary in-service function to be
performed by the geosynthetic and then calculating the required numerical value

of a particular property for that function. By dividing this value into the candidate material's allowable property value, a factor of safety (FS) results:

$$FS = \frac{\text{allowable (test) property}}{\text{required (design) property}} \qquad [1.1]$$

where

allowable property = numerical value based on a laboratory test that models the actual situation or is adjusted accordingly by reduction factors

required property = numerical value obtained from a design method that models the actual situation

FS = factor of safety against unknown loads and/or uncertainties in the analytical or testing process; sometimes called a global factor of safety

If the FS is sufficiently greater than 1.0, the candidate geosynthetic is acceptable. The above process can be repeated for a number of available products, and, if others are acceptable, then the final choice becomes one of availability and least cost. The individual steps in this process are as follows.

1 Assess the particular application, considering not only the candidate geosynthetic but also the material system on both sides of it.
2 Depending on the criticality of the situation (i.e. 'if it fails, what are the consequences?'), decide on a minimum FS value. Note that this value may be regulatory suggested or even imposed.
3 Decide on the material's primary function, the choices being separation, reinforcement, filtration, drainage or containment.
4 Calculate numerically the required property value in question on the basis of its primary function.
5 Test for, or otherwise obtain, the candidate geosynthetic's allowable value of this particular property (recall the previous discussion on the recommended use of MARVs).
6 Calculate the FS on the basis of the allowable property (Step 5) divided by required property (Step 4) per Equation [1.1].
7 Compare this FS with the required value decided upon in Step 2.
8 If not acceptable, repeat the process with a product with more appropriate properties.
9 If it is then acceptable, check whether any secondary function of the material is more critical.
10 Repeat the process for other available products and if more than one satisfy the FS requirement, select the product on the basis of least cost and availability.

Note that the design-by-function process can also be used to solve for the required property value:

$$\text{required (design) property} = \frac{\text{allowable (test) property}}{\text{FS}} \qquad [1.2]$$

The design-by-function approach obviously necessitates identifying the primary function that the geosynthetic is to serve; thus an overt awareness of the site-specific situation is necessary on the part of the designer.

It is important to recognize that the test property must be modified to account for field considerations which are not simulated in the laboratory test. For example, one takes a laboratory value of the candidate material and then reduces it for aspects of the testing which did not simulate the anticipated field situation to arrive at an allowable value. Koerner (2005c) presents reduction factor values for reinforcement and flow rate applications insofar as installation damage, creep, degradation, intrusion, clogging, etc., are concerned. See Table 1.3 for strength related and Table 1.4 for flow rate applications. These values are multiplied together (assuming worst-case synergy) and then divided into the laboratory (or ultimate) measured value. This methodology for strength and flow problems is given by

$$T_{allow} = \frac{T_{ult}}{RF_{ID} \times RF_{CR} \times RF_{CBD}} \qquad [1.3]$$

where

T_{allow} = allowable tensile strength
T_{ult} = ultimate tensile strength
RF_{ID} = reduction factor for installation damage
RF_{CR} = reduction factor for creep
RF_{CBD} = reduction factor for chemical and biological degradation

and for flow problems by

$$q_{allow} = \frac{q_{ult}}{RF_{CR} \times RF_{IN} \times RF_{CC} \times RF_{BC}} \qquad [1.4]$$

where

q_{allow} = allowable flow rate
q_{ult} = ultimate flow rate
RF_{CR} = reduction factor for creep reduction of void space
RF_{IN} = reduction factor for adjacent materials intruding into the geocomposite's void space
RF_{CC} = reduction factor for chemical clogging
RF_{BC} = reduction factor for biological clogging

1.4   Possible future practice in geosynthetic design

On the horizon there appear to be two possible extensions of the present status of geosynthetic materials design. One is the use of risk assessment via probability

Table 1.3 Recommended strength reduction factor values [after Koerner (2005c)]

	Range of reduction factor values		
Area	Installation damage	Creep[a]	Chemical–Biological degradation[b]
Separation	1.1–2.5	1.5–2.5	1.0–1.5
Cushioning	1.1–2.0	1.2–1.5	1.0–2.0
Unpaved roads	1.1–2.0	1.5–2.5	1.0–1.5
Walls	1.1–2.0	2.0–4.0	1.0–1.5
Embankments	1.1–2.0	2.0–3.5	1.0–1.5
Bearing and foundations	1.1–2.0	2.0–4.0	1.0–1.5
Slope stabilization	1.1–1.5	2.0–3.0	1.0–1.5
Pavement overlays	1.1–1.5	1.0–2.0	1.0–1.5
Railroads	1.5–3.0	1.0–1.5	1.5–2.0
Flexible forms	1.1–1.5	1.5–3.0	1.0–1.5
Silt fences	1.1–1.5	1.5–2.5	1.0–1.5

[a]The low end of the range refers to applications which have relatively short service lifetimes and/or situations where creep deformations are not critical to the overall system performance.
[b]Some authors have listed biological degradation as a separate reduction factor. There is no evidence, however, of such degradation for the typical polymers used to manufacture geotextiles. Thus, it is currently included with chemical degradation as a combined reduction factor.

Table 1.4 Recommended flow rate reduction factors [after Koerner (2005c)]

Application area	Range of reduction factor values			
	RF_{CR}[a]	RF_{IN}	RF_{CC}	RF_{BC}
Sport fields	1.0–1.5	1.0–1.2	1.0–1.2	1.1–1.3
Capillary breaks	1.0–1.2	1.1–1.3	1.1–1.5	1.1–1.3
Roof and plaza decks	1.0–1.2	1.2–1.4	1.0–1.2	1.1–1.3
Retaining walls, seeping rock, and soil slopes	1.2–1.4	1.3–1.5	1.1–1.5	1.0–1.5
Drainage blankets	1.2–1.4	1.3–1.5	1.0–1.2	1.0–1.2
Infiltrating water drainage for landfill covers	1.1–1.4	1.3–1.5	1.0–1.2	1.5–2.0
Secondary leachate collection (landfills)	1.4–2.0	1.5–2.0	1.5–2.0	1.5–2.0
Primary leachate collection (landfills)	1.4–2.0	1.5–2.0	1.5–2.0	1.5–2.0
Wick drains (prefabricated vertical drains)	1.0–2.5	1.5–2.5	1.0–1.2	1.0–1.2
Highway edge drains	1.5–3.0	1.2–1.8	1.1–5.0	1.0–1.2

[a]Creep values are sensitive to the core structure and to the density of the resin used. Creep of the covering geotextile(s) is a product-specific issue. The magnitude of the applied load is of major importance in both situations.

theory such that the FS value is accompanied by an associated probability of failure (P_f); the other is a technique known as load and resistance factor design (LRFD). Each will be briefly described, as well as their interrelationship to one another.

1.4.1   Probability of failure in geosynthetic design

As indicated in the FS equation given previously (Equation [1.1]), the *allowable value* invariably comes from testing of laboratory specimens for the product under consideration. The statistics (mean and standard deviation) of such testing are at present available through the GAI-LAP proficiency test program (Koerner, 1996, 2005a). Allen (2002) gave additional insight in this regard from the perspective of an individual laboratory. The *required value* consists of both geometric and load values. In general, the geometric values are well defined. The load values, however, are very subjective. Live loads including hydraulic and seismic loads are perhaps the variables with the greatest statistical variation of all required input variables. (For this reason consultants sometimes use upper-bound values for use in designs that are particularly sensitive and critical. However, with probability analysis this approach is not needed, nor is it appropriate.)

Upon having the allowable and required values for a particular problem, the calculation process for FS values is exactly as previously described. Computer codes are available for a number of strength- and hydraulic-related applications. Such computer codes, and the theories upon which they are based, usually have great accuracy in comparison with the input variables. Nevertheless, the result of this entire process is to generate a FS value greater than unity. How much greater depends upon the designer's confidence in the input variables versus the implications of failure or, at the minimum, unsatisfactory performance. Yet, the traditional FS value can be nicely counterpointed with a P_f value, which is a form of risk assessment.

Risk assessment in the form of probability of failure, P_f, is not new. From a geotechnical perspective the book by Harr (1987) was probably the first complete treatise on the subject. Adding to this information base was the work of Christian *et al.* (1994). More recently, the US Army Corps of Engineers (1997, 1998) has been involved as well as the recent appearance of the book by Baecher and Christian (2003). Indeed, the effort is at present worldwide in its scope with many excellent references in addition to those noted.

Two situations have recently coalesced to make the probability-of-failure approach practical. The first is the database of the GAI-LAP program mentioned earlier. The second is the appearance of an article by Duncan (2000). The latter methodology will be briefly described since it is recommended in this regard.

Step 1   Assemble the mean value and standard deviations of all the major variables that are to be used in the design method.

Step 2   Calculate the most likely value of the FS, namely FS_{MLV}, using the mean

values. (This is, of course, standard design practice with the exception that values should not be artificially inflated as is sometimes done in practice, i.e. they should be actual mean values.)

Step 3   Calculate the standard deviation and coefficient of variation of the FS_{MLV} using plus and minus one standard deviation of all the test and design variables:

$$\sigma_{MLV} = \left[\left(\frac{\Delta FS_1}{2} \right)^2 + \left(\frac{\Delta FS_2}{2} \right)^2 + \left(\frac{\Delta FS_3}{2} \right)^2 + \cdots \right]^{\frac{1}{2}}$$ [1.5]

$$V_{MLV} = \frac{\sigma_{MLV}}{FS_{MLV}}$$ [1.6]

where

FS_{MLV}	=	most likely (or traditional) value of the FS
σ_{MLV}	=	standard deviation of the FS_{MLV}
V_{MLF}	=	coefficient of variation of the FS_{MLV}
ΔFS_i	=	$FS_i^+ - FS_i^-$ (for each variable)
FS_i^+	=	FS calculated with the mean value of specific variable increased by one standard deviation
FS_i^-	=	FS calculated with mean value of the specific variable decreased by one standard deviation

Note that, in calculating each FS_i^+ and FS_i^- value, all the other ΔFS_i variables are kept at their most likely mean values.

Step 4   With both FS_{MLV} and V_{MLF} known, the probability of failure, P_f, can be determined using tables, or by using an analytical approach given by Duncan (2000). The P_f value represents the reliability of the FS_{MLV}. For example, a value of $P_f = 0.04\%$ suggests that the situation will experience four failures in 10 000 similar circumstances.

Step 5   Assess the FS value in the light of the accompanying P_f value. This assessment is currently quite subjective. Obviously, the lower the P_f value, the better, with the situation approaching zero being no likelihood of failure. Relatively high values of P_f can be accepted depending on the duration and criticality of the site-specific application.

Having this information on P_f values, we are now in a position to compare them with acceptable values. Unfortunately, there is no consensus of acceptable values at this point in time. Koerner and Koerner (2001) made an initial attempt but the values that they provided were very restrictive and drew a considerable number of negative comments. Their initial table has been modified upwards and is given here as Table 1.5. The table is structured according to the primary function that the geosynthetic is to serve and the sensitivity of the application within that particular

Table 1.5 Suggested limiting probability of failure values compared with results from numerous example problems

Geosynthetic primary function	Consequence of failure %			Average P_f values[a] (%)
	Low	Typical	Serious	
Separation	7.0	1.5	0.5	0.54
Reinforcement	3.0	0.5	0.1	2.1
Filtration	5.0	1.0	0.3	5.1
Drainage	5.0	1.0	0.3	4.8
Containment	3.0	0.5	0.1	2.9

[a]These values were obtained using all the numerical examples in the textbook by Koerner (2005b).

function. Consequences of failure are ranked as being low, typical and serious with approximate definitions as follows:

- 'Low' refers to a remediation cost of US$100 000 or less;
- 'Typical' refers to a remediation cost of US$1 000 000 or less;
- 'Serious' refers to a remediation cost of more than US$1 000 000 and/or loss of life.

The average P_f values taken from the numerical examples in the paper by Koerner (2002) are superimposed on the last column of Table 1.5. It can be seen that there is a correlation with the acceptable values going from a low to serious consequence of failure. Obviously, much more thought and consideration should eventually be included in a table of this type. The paper by D'Hollander (2002) is valuable in this regard.

1.4.2   Load and reduction factor design

If one rearranges Equation [1.1] (together with the elimination of the FS value) in the form of an inequality, one has the basic concept of load and reduction factor design (LRFD). Thus, the required (design) property must be less than or equal to the allowable (test) property. Now, using load factors on the required property (to obtain worst-case conditions) and reduction factors on the ultimate property (to obtain allowable values), we have the desired LRFD formulation

$$\Sigma(LF_i \, D_{ni}) < (R_n/RF) \tag{1.7}$$

where

LF_i = load factors on each design element (all are 1.0 or greater)
D_{ni} = design value on each element
RF = resistance factors accounting for degradation, creep, etc. (all are 1.0 or greater)
R_n = ultimate resisting value from laboratory tests

As indicated, the left-hand side of the equation is the load side and the right-hand side is the resistance side. Recall from previous discussion in Section 3.2 that the resistance side is already practised in geosynthetics design. Thus, present geosynthetics design practice already accomplishes one half of LRFD. The other half is, however, far less defined or established and is not at present practised in geosynthetics design.

Scott *et al.* (2003) offer load factors in Table 1.6 and Table 1.7 for dead, live, wind and seismic design conditions. It is unfortunate that hydraulic loads are not specifically mentioned since the difference between a 1 h storm and a 100 year

Table 1.6 Load factors for the ultimate limit state, i.e. failure or collapse [after Scott *et al.* (2003)]

	Load factor							
	USA				Canada		Europe	
Load	AASHTO[a] (1998)	ACI[a] (1999)	AISC[a] (1994)	API[a] (1993)	MOT[a] (1992)	NRC[a] (1995)	DGI[a] (1985)	ECS[a] (1995)
Dead	1.25–1.95	1.4	1.2–1–4	1.1–1.3	1.1–1.5	1.25	1.0	1.0–1.35
Live	1.35–1.75	1.7	1.6	1.1–1.5	1.15–1.4	1.5	1.3	1.3–1.5
Wind	1.4	1.3	1.3	1.2–1.35	1.3	1.5	1.3	1.3–1.5
Seismic	1.0	1.4	1.0	0.9	1.3	1.0	1.0	1.0

[a]AASHTO, American Association of State ̈lighway and Tranșortation Officials; ACI, American Concrete Institute; AISC, American Institute of Steel Construction; API, American Petroleum Institute, MOT, Ministry of Transportation (Canada); NRC, National Research Council of Canada; DGI, Danish Geotechnical Institute; ECS, European Committee for Standardisation.

Table 1.7 Load factors for the serviceability limit state, i.e. excessive deformation [after Scott *et al.* (2003)]

	Load factor						
	USA			Canada		Europe	
Load	AASHTO[a] (1998)	ACI[a] (1999)	AISC[a] (1994)	MOT[a] (1992)	NRC (1995)	DGI[a] (1985)	ECS[a] (1995)
Dead	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Live	1.0	1.0	1.0	0.75	1.0	N/A[b]	1.0
Wind	0.3	1.0	1.0	0.7	1.0	N/A[b]	1.0

[a]AASHTO, American Association of State Highway and Transportation Officials; ACI, American Concrete Institute; AISC, American Institute of Steel Construction; API, American Petroleum Institute, MOT, Ministry of Transportation (Canada); NRC, National Research Council of Canada; DGI, Danish Geotechnical Institute; ECS, European Committee for Standardisation.
[b]N/A, not applicable, values for transient loads are given in the structural code.

storm (or even maximum probable precipitation) is enormous. Nevertheless, Table 1.6 for failure, or collapse, situations is very helpful. LRFD also encompasses serviceability issues and Table 1.7 gives the load factors for such conditions. As an example, a geogrid-reinforced retaining wall would use Table 1.6 to prevent collapse, and Table 1.7 to prevent excessive wall deformation.

There are many additional aspects of LRFD and the worldwide literature is abundant in this regard. Suffice it to say that structural engineering designers are fully involved in LRFD and it is very possible that geotechnical (and geosynthetics) engineering designers might be encouraged, or even forced, to follow accordingly. Time will tell in this regard.

1.4.3   Interrelationships of probability and load and reduction factor design

Probability and LRFD can be nicely counterpointed against one another, at least on a conceptual basis. Figure 1.2 attempts to do this in the form of probability curves of required load and resistance curves of the material. Figure 1.2(a) shows the case in which the probability curves of required values and resistance values do not overlap at all. This signifies that there is zero risk or likelihood of failure. Figure 1.2(b) shows the case when the curves just touch, which signifies that at the probability extremes there is still no likelihood of failure, but it is a limiting condition. Figure 1.2(c) shows the curves overlapping one another. The greater the overlap, the higher is the risk, or the likelihood of failure. While these concepts are clear, it is quite another matter to obtain the requisite data to draw the curves specifically and to generate numerical information. This area appears to be currently in a developing stage.

1.5   Summary and conclusions

This chapter on geosynthetics design has traced its origin, through the present status, and into possible future methods. Regarding the *past*, design by cost was the original procedure and (paradoxically) served reasonably well. From the earliest days it was tempered with manufacturers' specifications, but that was to be expected. The *present* status sees geosynthetics design taking two pathways: design by specification for customary and non-critical applications; design by function for site-specific and critical applications. Both are quite well positioned and can be considered as the state of the practice. The future of geosynthetics design promises the use of risk assessment via probability theory juxtaposed with LRFD. These techniques can be considered as the state of the art. How quickly this may, or may not, occur is uncertain but a considerable literature base is developing and our structural engineering design colleagues have fully embraced the concept. Clearly, geosynthetics designers should be aware of the details and nuances of the techniques and this brief introduction may help in this regard.
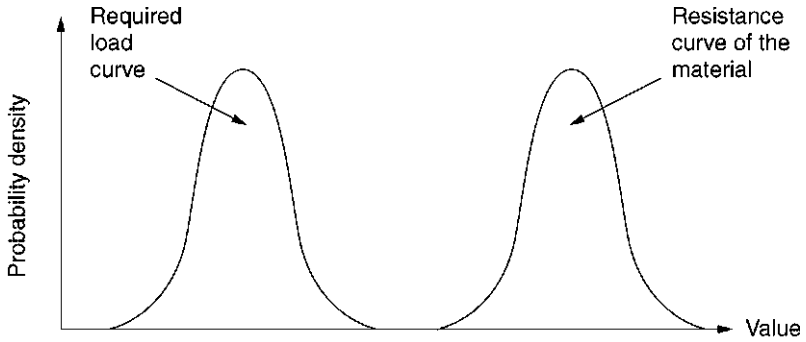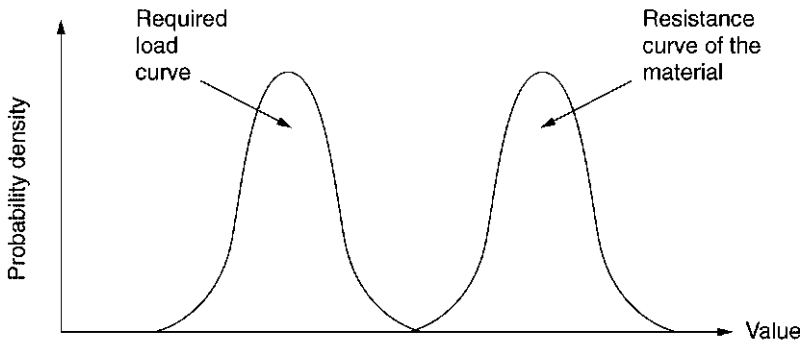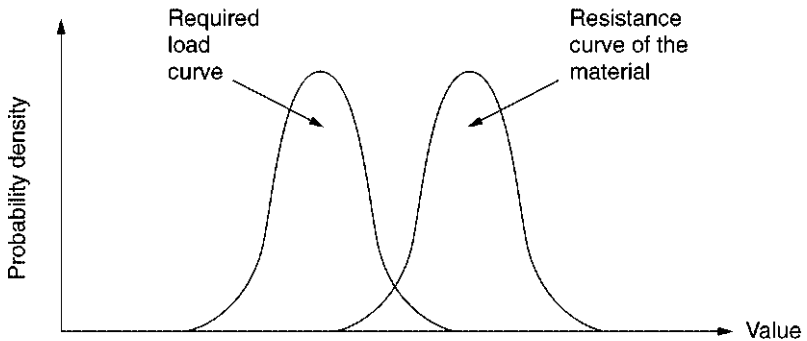
1.2 Contrasting probability curves to assess relative risk, i.e. graphical representation of the LRFD concept: (a) curves not intersecting, no possibility of failure; (b) curves just touching, zero risk of failure; (c) curves intersecting, finite risk of failure.

1.6   Acknowledgements

1.7   References

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2

The material properties of geosynthetics

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2.1   Introduction

This chapter describes the material properties of geosynthetics that are important to their use in various applications and methods for measurement of those properties. Geosynthetic material properties and test methods for the measurement of those properties have arisen first from previously existing materials that resemble geosynthetics, such as textile materials used in the garment trade and plastic materials used in various industrial applications. As functions and applications of geosynthetics have been identified and developed, properties and test methods have followed to aid in proper design and construction. For example, materials used for reinforcement depend heavily on mechanical properties while filtration and drainage functions depend on hydraulic properties. Most applications involve transport and storage of materials, construction in relatively harsh environments and the necessity for a long service life, for which endurance and durability properties are important. Given the relatively young age of geosynthetic materials and their applications, and the time needed for the development and standardization of test methods, many test methods are not standardized. Additionally, the status of these test methods is constantly evolving as tests are developed, standardized and refined.

Geosynthetic materials are time and temperature dependent. This imposes special considerations for testing conditions to ensure consistency between testing laboratories and applicability to field conditions. The properties of geosynthetics are often direction dependent, meaning that the direction in which they are tested will influence the values of certain properties.

The properties of geosynthetics are typically grouped into those used for quality assurance (QA) or quality control (QC) and those used for design. These two groups of properties are sometimes referred to as index and performance properties, respectively. These names have also taken on other meanings, such as index properties being those obtained from tests on the geosynthetic itself as isolated from any surrounding soil, and performance properties being those determined from tests where the geosynthetic is in contact with a subject soil.

In this chapter, properties and test methods are grouped into the categories of physical, mechanical, hydraulic, endurance and degradation properties. The chapter concludes with information given on future trends and sources for obtaining further information.

2.2   Physical properties

Physical properties of geosynthetics are basic properties related to the composition of the materials used to fabricate the geosynthetic and include the type of structure, specific gravity, mass per unit area, thickness and stiffness. The type of structure of a geosynthetic describes the physical make-up of the geosynthetic resulting from the process used to manufacture the material. The structure of the geosynthetic often dictates the application area for which the material is appropriate. For example, a uniaxial geogrid is appropriate for applications where load is expected in one principal direction of the material, such as in a long slope or retaining wall. The geosynthetic structure is most often described for geogrids. The structure of geogrids of greatest importance is that associated with the manufacturing process used to form the junctions of the geogrid, with examples including woven, integral and welded junctions. Structure can also be described for geotextiles where the two main types of structure include woven and non-woven geotextiles.

The specific gravity of a geosynthetic is measured on the basic polymeric material or materials used to form the geosynthetic. The specific gravity is defined conventionally as the ratio of the material's unit volume weight to that of distilled, de-aerated water at a standard temperature. Ranges of values for the specific gravity of commonly used geosynthetic polymers are listed in Table 2.1. The specific gravity of the geosynthetic polymer is important in applications where the geosynthetic will be placed underwater where polymers with values of specific gravity less than one will require weighting in order to sink the material into position.

Mass per unit area describes the mass (usually in units of grams) of a material per unit area (generally in square metres) and should be measured with no tension applied to the material. Typical values for geotextiles lie between 130 and 700 g/m² while for geogrids the values range from 200 to 1000 g/m².

The thickness of a geosynthetic is measured as the distance between the extreme upper and lower surfaces of the material. For geotextiles, this distance is measured

Table 2.1 Specific gravities of common geosynthetic polymers

Polymer	Specific gravity
Polyamide	1.05–1.14
Polyester	1.22–1.38
Polyethylene	0.90–0.96
Polypropylene	0.91

while a specified pressure is applied to the material. Thicknesses of geotextiles range from 0.25 to 7.5 mm. The thickness of common geomembranes used today is 0.5 mm.

The physical property of stiffness refers to the flexibility of the material and is not a description of the mechanical property of stiffness which describes the material's load–strain modulus. The flexibility of a geosynthetic is determined by allowing the material to bend under its own weight as it is being slid over the edge of a table. The properties of flexural stiffness or rigidity describe the material's capability of providing a suitable working platform during installation and is an important property when installation is performed over soft soil sites.

## 2.3   Mechanical properties

Mechanical properties of geosynthetics relate to applications where the geosynthetic is required to bear a load or to undergo a deformation. During the construction of facilities containing geosynthetics, loads perpendicular to the plane of the geosynthetic can be introduced as the material is placed on irregular surfaces with soil compacted on top. These loads can be significant and can often dictate the mechanical properties specified for the geosynthetic. Failure to specify appropriate mechanical properties for the construction conditions may result in physical damage (i.e. punctures, tears and rips) to the geosynthetic, which then may compromise the mechanical properties needed for proper functioning of the application.

Loading can also be applied in the plane of the geosynthetic resulting in tension of the material. This type of loading is generally associated with the function or operation of the constructed facility and where the mechanical properties of the geosynthetic are typically used in the design of the facility. Mechanical properties pertaining to the shearing resistance between the geosynthetic and the surrounding soil are also important as this resistance is responsible for transferring load from the soil into tensile load in the geosynthetic.

Mechanical properties of geosynthetics are often categorized as either index or performance properties. Index properties refer to those determined on the geosynthetic itself in the absence of any surrounding soil. These properties are sometimes referred to as in-isolation properties. Performance properties involve those determined in the presence of a standard soil or the site-specific soil.

2.3.1   Tensile properties

Tensile properties of geosynthetics are generally the most important set of properties, particularly for applications where reinforcement is the primary function of the geosynthetic. Tensile properties are used for quality QC/QA and as design parameters for various applications. The tests used for QC and QA purposes tend to be simpler and less time consuming to perform and interpret than those used to
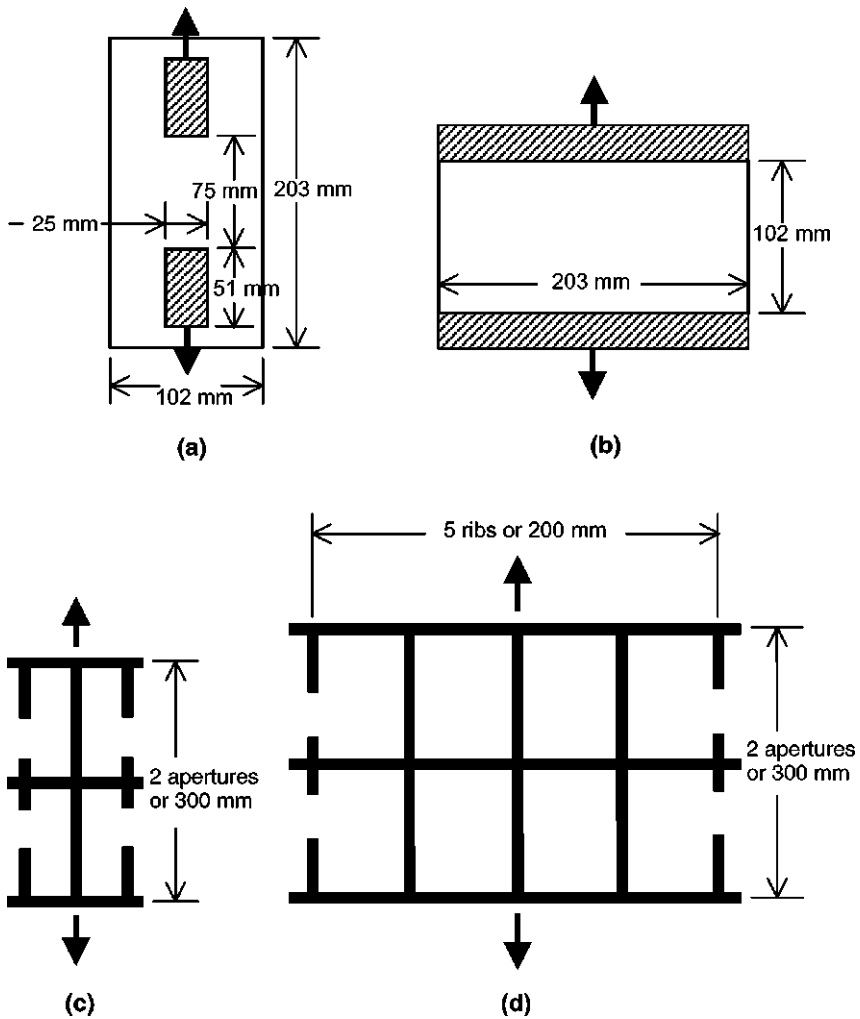
2.1 Specimen sizes for various tensile tests: (a) grab; (b) geotextile wide width; (c) geogrid wide width, method A; (d) geogrid wide width, method B and C.

generate design parameters. Figure 2.1 shows a schematic diagram of different types of tensile tests. Figure 2.1(a) is known as a grab tensile test with ASTM test designation ASTM D4632. The grab tensile test is performed on geotextiles and provides QC and QA information that can only be used comparatively between geotextiles with similar structures since each material structure performs in a unique manner in this test. The test is performed by gripping the specimen as shown in Fig. 2.1(a) and applying a continuously increasing load until rupture occurs. The load at rupture and the corresponding elongation are measured and

reported. The grab tension test also represents loading that may occur in the field because of the spreading action of two pieces of coarse aggregate in contact with the geosynthetic.

Figure 2.1(b), Fig. 2.1(c) and Fig. 2.1(d) illustrate tension tests used to determine tensile design properties of geotextiles and geogrids. Figure 2.1(b) shows the test specimen size for wide-width tension tests on geotextiles (ASTM D4595). For geogrids, either multirib specimens (Fig. 2.1(c)) or single-rib (Fig. 2.1(d)) may be used according to ASTM D6637. For the tests shown in Fig. 2.1(b), Fig. 2.1(c) and Fig. 2.1(d), the ultimate strength, strain at failure and modulus are typically determined. The strength and modulus are typically expressed in terms of a load per unit width of material rather than a stress since stress requires the definition of material thickness, which is generally difficult to describe for most geosynthetics and does not remain constant during tensile loading. The modulus can be defined as an initial modulus, a secant modulus or an offset tangent modulus. Modulus values are very dependent on how the specimen is conditioned at the beginning of the test and standardized procedures should be followed to ensure comparability of results. Since geosynthetics are rate and temperature dependent, standards should also be followed with respect to these test variables. Geosynthetic materials are typically direction dependent, meaning that tension tests should be performed in both principal material directions.

For tests where elongation or strain is measured, displacement measurement techniques become important. If displacement is measured as movement between the grips, then slippage within the grips should not occur. For geotextiles with strengths less than 90 kN/m, conventional clamping grips are usually sufficient. Wedge grips may be good for materials with strengths between 90 and 180 kN/m. For materials with strengths exceeding 180 kN/m, roller grips are typically used.

The tension tests described above are performed without any soil covering the geosynthetic and are therefore known as in-isolation or in-air tests. Soil covering the geosynthetic provides confinement to the material, which in general has the effect of increasing the material's modulus and strength. Increases in modulus and strength are most significant for non-woven geotextiles, but also noticeable for woven geotextiles and geogrids (Elias *et al.*, 1998) This results from internal friction between fibres or yarns, alignment of curved fibres or yarns, and interlocking of soil within openings or apertures of geosynthetics (Elias *et al.*, 1998).

The first two factors imply an effect on the intrinsic load–strain properties of the geosynthetic, while the third factor reflects interaction between the geosynthetic and the soil with the measured load–strain properties thereby reflecting the coupled responses of the material itself and its interaction with surrounding soil. For analyses where the geosynthetic and surrounding soil is treated as a coupled system, use of load–strain properties from confined tension tests are appropriate. For analyses where the intrinsic properties of the geosynthetic are uncoupled from the interaction between the geosynthetic and the soil, then the use of load–strain properties from in-air tests are more appropriate. An example of an uncoupled

analysis is one using the finite element method where the load–strain properties of the geosynthetic are specified together with interface shear properties (confinement-dependent shear stiffness and friction angle) describing interaction between the geosynthetic and the surrounding soil.

Biaxial tension tests have been performed to assess material load–strain response for applications where load is applied simultaneously in two directions of the material (McGown and Kupec, 2004). Biaxial tests are performed by forming specimens in the shape of a cross and applying load simultaneously in the machine and cross-machine directions. The results can be used to assess strength and modulus under conditions of biaxial loading or to compute Poisson's ratio for use in advanced analyses (Perkins *et al.*, 2004).

2.3.2   Compressibility

The compressibility of geosynthetics is defined as the relationship between the material thickness as a function of applied normal stress and is a test most appropriate for geotextiles and geonets that need to maintain a certain thickness to ensure water transmissivity. For geotextiles, non-woven needle-punched materials tend to be the most compressible, while woven and non-woven heat bonded materials show small levels of compressibility. Some materials, especially geonets, tend to experience small levels of compression prior to collapse. For these materials, the compression strength is of most importance.

2.3.3   Seam strength

Geosynthetics are generally manufactured in rolls of a given width and length. Particular jobs may require a coverage area that exceeds the size of the manufactured roll and where adjoining rolls may be mechanically or chemically jointed either in the field or in the manufacturing plant. Geosynthetics may be jointed by sewing, stapling, glueing or melting, or by the use of bodkin rods extending through the apertures of geogrids. Tensile tests are performed typically on widewidth specimens to assess the tensile strength of seams. The strength of the seam is compared with the tensile strength of the geosynthetic itself to arrive at a seam strength efficiency. Efficiencies of 100% are possible for geotextiles with tensile strengths less than 44 kN/m and drop to 50% for materials with strengths greater than 440 kN/m (Koerner, 2006).

2.3.4   Burst strength

Burst strength tests are performed on geotextiles and geomembranes by causing a circular piece of material clamped around its perimeter to stretch into the shape of a hemisphere by the application of pressure on one side of the material. The material stretches in tension until rupture occurs. In the field, geotextiles may
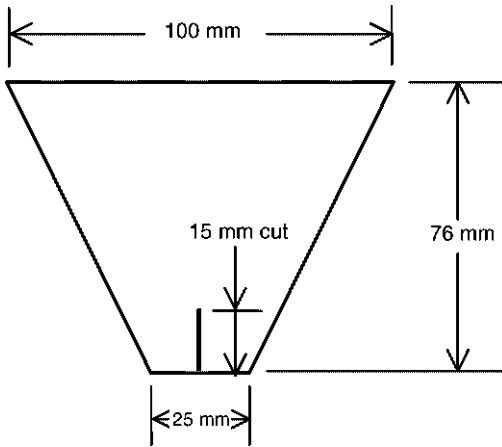
2.2 Specimen shape for the trapezoid tear test (ASTM D4533).

experience this type of loading when used as a separator between soft subgrade and coarse aggregate. As subgrade is squeezed upwards between voids of the coarse aggregate, the geotextile takes on a hemispherical shape similar to that experienced in the burst strength test. Geomembranes may experience this kind of loading in landfill applications where a void might open up beneath the geomembrane layer.

2.3.5   Tear strength

During the installation of geotextiles, stresses may be imposed which cause tears to initiate and propagate. Several types of tests have been developed to describe the tearing resistance of geotextiles. The most common test is the trapezoidal tear test (ASTM D4533). In this test, the specimen is formed in the shape of a trapezoid, as shown in Figure 2.2, and a 15-mm cut is made along one end of the specimen. The two non-parallel sides of the specimen are gripped in parallel grips of a tension load frame with the two grips aligned parallel to the cut made in the material and separated by a distance of 25 mm. This is accomplished by allowing folds to occur in the material greater than 25 mm in width. Tension is then applied and the cut in the material propagates across the specimen as individual strands of the geotextile are torn. Minimum values of tear strength are generally specified to control installation damage of geotextiles.

2.3.6   Puncture strength

In addition to the possibility of tears during installation, geotextiles and geomembranes can experience punctures from rocks, roots, sticks or other debris. A test has been developed to measure the puncture resistance of these materials

(ASTM D4833) where a steel rod of 8 mm diameter is used to puncture a geo-synthetic stretched and clamped firmly over a cylinder of 45 mm inside diameter. The force necessary to cause the rod to puncture through the material is known as the puncture resistance.

2.3.7   Friction

An adaptation of the direct shear test for soils is used to measure the shearing resistance or friction between geosynthetics and soils and between two layers of geosynthetics. Test method ASTM D5321 calls for a shear box measuring 300 mm by 300 mm. The shear box is configured to contain soil in the bottom half and the geosynthetic clamped to the top half of the box. Within the confines of the top half of the box and above the clamped geosynthetic, soil or a textured block may be used to transfer shear load evenly across the face of the geosynthetic.

The test is performed similarly to a direct shear test on soil with normal confinement being applied to the box prior to applying a horizontal shear displace-ment that causes the two halves of the box to displace and shear relative to each other. The shear load is measured and divided by the area of shear and plotted against the horizontal shear displacement. The ultimate shearing resistance is plotted against the normal stress confinement for several tests at different levels of confinement. A Mohr–Coulomb failure criterion is then obtained from these data. Values of cohesion and friction angle are compared with those obtained for the soil itself to arrive at shear strength parameter efficiencies. Similar procedures are followed for tests performed between two layers of geosynthetics. Results from these tests have applications in landfills where geosynthetic sheets are in contact with soil materials or other geosynthetic sheets on slopes where sliding can occur.

2.3.8   Pull-out resistance

Pull-out tests are typically performed to assess the anchorage or pull-out capacity of geosynthetics. This capacity is important in situations such as retaining walls, slopes and bridging over voids, where the geosynthetic is anchored into stable ground that is outside the zone of failure. The test can also be used to assess interface shear resistance and stiffness properties for applications where soil is moving relative to the geosynthetic, such as in reinforced roadways.

The test is performed in an apparatus described by ASTM D6706 and shown in Fig. 2.3, where the dimensions shown are minimum dimensions that may need to be increased depending on the structure of the geosynthetic, particle size of the soil, and provisions for reducing side-wall friction. Normal stress confinement is provided by an air bag placed between the top of the soil and a reaction frame. A sleeve is fitted to the front of the box where the geosynthetic enters and extends a minimum of 150 mm into the box. The purpose of the sleeve is to reduce the amount of normal stress generated along the front wall of the box as the geosynthetic
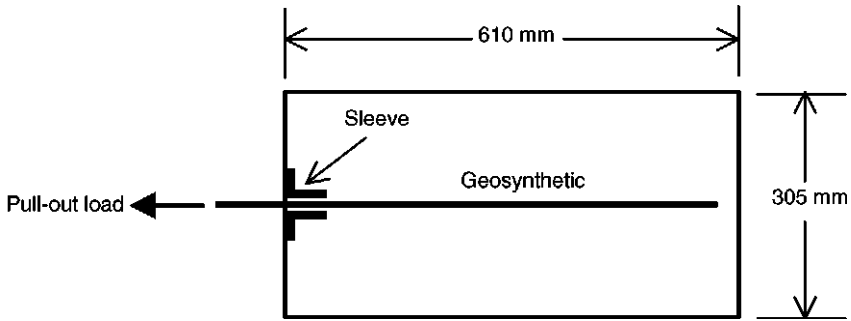
2.3 Apparatus for pull-out testing (ASTM D6706).

is being pulled out. Measurements during testing typically consist of applied pull-out load, horizontal displacement of the front of the geosynthetic and horizontal displacement of the geosynthetic at several locations along the material's length. The later is accomplished with the use of a telltale, which consists of a protected wire attached to the measurement point on the geosynthetic and extending out from the back of the box where it is attached to a displacement-sensing device.

The pull-out resistance or anchorage capacity is calculated as a line load taken as the force necessary to cause pull-out divided by the width of the specimen. This force is typically used to compute an interaction coefficient, which is essentially the ratio of the friction angle of the geosynthetic–soil interface to that of the soil itself. To make the calculations described above, it is important that sufficiently large displacement occurs along the entire embedment length of the geosynthetic such that the ultimate shearing resistance is fully mobilized. For long embedment lengths and large normal stress confinement, this may not be the case and the test must then be interpreted as a boundary-value problem where several methods have been proposed (Juran and Chen, 1988; Yuan and Chua, 1991; Perkins and Cuelho, 1999).

2.4   Hydraulic properties

Hydraulic properties of geosynthetics are important in applications where the material is used to convey or prevent the flow of liquids and gases. Geotextiles, geomembranes, geonets, geosynthetic clay liners and drainage composites are all materials that are called upon to perform these functions. Applications include drainage materials behind walls and within slopes, roadways and landfills, filtration materials within roads and around drainage trenches, and liquid and gas containment for ponds, for canals and within landfills.

2.4.1   Porosity

The porosity is a convenient property in that it has the same definition (the ratio of

the void volume to the total volume) as that used for soils. The void volume, however, is difficult to measure, so the porosity has to be calculated from other physical properties (mass per unit area, density and thickness). As a result, other measures, including the percentage open area and apparent opening size (AOS), related to the porosity but more easily measured and more directly related to particular applications have been developed.

2.4.2   Percentage open area

The percentage open area is a property that is specified and measured for woven geotextiles and is a property that describes the ratio of the open area to the total area. The open area is typically measured by shining light through the material and projecting this light on to a screen that can be used to measure and sum the open areas. This test is not appropriate for non-woven geotextiles since the overlap of the weaves prevents most light from shining through even though liquid transmission is still very possible.

2.4.3   Apparent opening size

The AOS test was first developed for woven geotextiles but is now also used for non-woven materials. The test is described by ASTM D4751 and consists of passing glass beads of successively larger diameter through the material until only 5% of the beads pass through. The size of the beads in millimetres at which 5% passes is known as O_{95}. The corresponding size in the US sieve size is the AOS. The AOS or O_{95} represents the largest particle that would effectively pass through the geotextile. The equivalent opening size (EOS) has the same meaning as the AOS but can be specified for other percentage passing values, such as O_{50} or O_{90}. The AOS is typically specified in conjunction with requirements for filtration, with proper specification providing for soil retention without pore space clogging.

2.4.4   Permittivity

The permittivity describes the ability for fluid flow across the plane of the geosynthetic. It is formally defined as the cross-plane permeability divided by the thickness of the geosynthetic. ASTM D4491 describes a constant-head and a falling-head permeability test that is used to define permittivity under zero-normal-stress confinement. These tests are conducted like similar tests on soils only with the apparatus sized to accommodate the flows associated with geotextiles. Values of cross-plane permeability for geotextiles range from 0.0008 to 0.23 cm/s with a corresponding range of permittivities ranging from 0.02 to 2.1 s^{-1}. Non-woven needle-punched geotextiles experience a slight to moderate decrease in permittivity as the normal stress confinement on the material is increased. Geonets have values of permeability of the order of 1–10 cm/s. Geomembranes have a

value of 10^{-11} cm/s while geosynthetic clay liners have saturated values ranging from 5.0×10^{-9} to 1.0×10^{-10} cm/s.

2.4.5   Transmissivity

Transmissivity describes the ability for fluid flow within the plane of the material and is defined as the in-plane permeability multiplied by the material thickness. The test method ASTM D4716 describes a constant-head test that can be conducted under varying normal stress confinement. Fluid is caused to flow one-dimensionally in the plane of the material from one end to another under constant-head conditions. Values of in-plane permeability of geotextiles range from 0.0006 to 0.04 cm/s with corresponding transmissivity values ranging from 3.0×10^{-9} to 2.0×10^{-6} m^2/s.

2.4.6   Soil retention

Geotextiles are often used as fences to retain fines as turbid water flows from disturbed areas to streams, ponds or lakes. The ability of the geotextile to allow water flow while retaining soil particles is determined by ASTM D5141. In this test, the site-specific soil is mixed with water to form a slurry and is poured into a flume box set on a 8% slope with the downstream end covered by the candidate geotextile. The flow rate of the soil–water mixture passing through the geotextile is measured together with the amount of fines. These measurements allow for the slurry flow rate and retention efficiency to be determined. The process is repeated at least three times to determine the degree of clogging that occurs.

2.5   Endurance properties

Endurance properties of geosynthetics focus on how short-term properties are affected by time during the service life of the facility. Issues of endurance arise as the material is installed, while the load is sustained, and while fluid flow is experienced.

2.5.1   Installation damage

The deformations and stresses experienced by geosynthetics during installation can be more severe than the actual design stresses for the intended application and arise from the placement and compaction of overlying fill. Damage may occur in the form of holes, tears and ruptures, which influences the mechanical and hydraulic properties of the material.

Criteria for survivability of geosynthetics have been developed by AASHTO M288-96. These criteria consider the construction conditions of the subgrade, the contact pressure provided by the construction equipment and the compacted base

course thickness to be used. Based on the combination of these conditions, the survivability level of the geosynthetic is assessed. The survivability level is then expressed in terms of certain geosynthetic index properties. Field trials can also be performed using the site-specific ground conditions, construction equipment and procedures with the installed material exhumed immediately after placement to assess damage.

2.5.2   Creep and stress relaxation

Creep is defined as the elongation of a material under a constant load. Stress relaxation is the reduction in (relaxation of) stress when a material is loaded and then held at a constant level of strain. Creep is an important consideration in design as large levels of creep can lead to excessive deformation of reinforced structures or possible creep rupture of geosynthetics. Stress relaxation can result in more load being taken up by the soil, which may produce unsafe conditions for situations where the soil is close to failure.

Creep and stress relaxation are interrelated and are dependent on the viscous properties of the geosynthetic. Viscous properties of geosynthetics are dependent on the type of polymer. Creep and stress relaxation are most significant for geosynthetics composed of polypropylene and polyethylene and less significant for polyester and polyamide geosynthetics. The magnitude of creep and stress relaxation increase as the temperature, magnitude of load and time increase (Greenwood and Myles, 1986). Cyclic loading can also produce creep and stress relaxation since cyclic loading is another form of sustained loading.

ASTM D5262 describes a test method for determining elongation due to creep. The test is relatively simple to conduct and involves placing hanging weights on a geosynthetic specimen and making periodic measurements of elongation. A stress relaxation test is more difficult to conduct in that a fixed displacement must be applied and the load over time must be monitored. This implies the use of a displacement controlled device typically with electronic load-sensing devices.

2.5.3   Abrasion

The abrasion of geosynthetics is defined as the wearing away of any part of a material by rubbing against another surface. Excessive abrasion can lead to a loss of properties, e.g. strength, that are needed for proper functioning. The most pertinent ASTM specification for abrasion testing is ASTM D4886 and is used for geotextiles. In this test, the specimen is mounted on a stationary horizontal platform and is rubbed by an abradant (typically sandpaper) mounted on a flat block. The vertical pressure is controlled while the block containing the abradant is moved back and forth along a uniaxial path. Resistance to abrasion is expressed as a percentage of the original strength of the material. While this test is technically valid for geogrids and geomembranes, it has only been evaluated for

geotextiles and a larger database of results are needed before it can be used for other materials.

2.5.4   Clogging

Clogging is an endurance property most pertinent to geotextiles. Clogging can occur over the long term as fluid flows through the geotextile carrying with it suspended particles that become lodged within the material. Physical tests have been devised and evaluated to match these long-term conditions and using site specific soils. These tests suffer from the large amount of time that it takes to conduct the test.

The gradient ratio test (ASTM D5101) has been adopted to reduce the amount of testing time associated with other more direct physical tests. The test is set-up within a vertical column with a layer of soil placed on top of a geotextile. Vertical flow is maintained through the soil–geotextile system. The hydraulic gradient is measured as the head loss divided by the flow length for two regions of the system. The first region contains the geotextile and 1 in of soil above the geotextile. The second region contains 2 in of soil and extends over a length of 1 in above the geotextile to 3 in above the geotextile. The ratio of these gradients is used to assess the clogging potential of the system, with values of three or greater indicating the potential for clogging.

The structure of the geotextile influences the possibility for the formation of a soil cake on the upstream side of the material. If gaps exist between the geotextile and the soil, soil fines tend to collect within these gaps and form a soil cake. This leads to clogging of the surface of the geotextile and is referred to as blinding. Materials with a tortuous surface, such as non-woven needle-punched materials, tend to conform more to the irregular surface of a soil, form less gaps and show less blinding (Giroud, 1994).

2.6   Degradation

Degradation of a geosynthetic results from fundamental changes of the polymer at the molecular level from its as-fabricated state. Degradation processes leading to ageing of the polymer include molecular chain scission, bond breaking, cross-linking and the extraction of components. Chemical fingerprinting methods are available that detect polymer changes: however, these methods are expensive to perform. Common and less expensive tests such as tensile strength and elongation are therefore conducted to assess the impact of these changes.

2.6.1   Temperature

Increasing the temperature has the principal effect of accelerating other degrada-tion mechanisms. When viewed as a degradation mechanism, temperature is

therefore generally associated with other mechanisms such as those involving oxidation, hydrolysis, chemical, radioactive, biological and ultraviolet (UV) light processes. High temperatures approaching the melting point of the polymer (165 ℃ for polypropylene and 125 ℃ for polyethylene) are an obvious consideration and should be avoided. Low temperatures can influence the brittleness and impact strength of geosynthetics, which influences their workability and potential for damage during installation.

2.6.2   Oxidation

Oxidation is a reactive process by which the elements of a material lose electrons when exposed to oxygen and its valence is correspondingly increased. In geosynthetics, this reaction leads to a fundamental change in the polymer and a degradation of the properties of the material. Polypropylene and polyethylene are generally the most susceptible polymers to the oxidation process. A test method used for exposing geosynthetics to the oxidation process is ASTM D794 specified for plastics. This test method uses an oven to apply heat with a continuous fresh-air flow. The test is carried out to a point where there is an appreciable change in appearance, weight, dimension or other specified properties pertinent to the application in question.

2.6.3   Hydrolysis

Hydrolysis is a process by which a chemical compound decomposes by its reaction with water. Geotextiles can experience hydrolysis degradation by internal or external yarn degradation (Hsuan *et al.*, 1993), which becomes more significant for polyester materials and for liquids with a high alkalinity. Polyamides can be affected by liquids with very low pH values. To evaluate the effect of hydrolysis, simple tests are conducted where a material is immersed in a liquid having a pH level of interest and at temperatures of 20 °C and 50 °C. The strength of the material is determined after a certain amount of immersion time and compared with initial values to detect degradation levels.

2.6.4   Chemical degradation

Chemical degradation involves the change in material properties when the geosynthetic is immersed in various chemicals of interest. ASTM D5322 describes a laboratory test procedure for immersing geosynthetics in chemical liquids. Provisions are given for controlling the temperature, the pressure and the circulation of the solution. ASTM D5496 describes a procedure for immersion of field specimens. These tests are most often used in association with geosynthetics used in landfills and as liners in reservoirs, ponds and impoundments.

2.6.5   Ultraviolet light

UV light is the component of light from the sun with wavelengths shorter than 400 nm. Photons of UV light can break down the chemical bonds (bond scission) of the polymer and lead to degradation of properties. Polyethylene is the most susceptible to UV degradation and can show a 50% strength loss within 4–24 weeks of exposure. Carbon black and other stabilizers are used to provide the polymer with UV protection, which generally means that geosynthetics that are light in colour are more susceptible. Since most geosynthetics are buried in the ground, the issue of UV degradation is important only during transport, storage and construction. During transport and storage, precautions are taken to wrap geosynthetic rolls in a protective cover to prevent UV damage.

For situations where it is important to assess the degradation of geosynthetics to long-term UV exposure, tests can be carried out by exposing geosynthetics to natural or artificial radiation. Sources of artificial radiation includes xenon arc lighting and fluorescent lighting.

2.7   Sources of further information

Information in this chapter has drawn upon several sources of material that serve as founding material for this subject. The textbook by Koerner (2006) was first published in 1986 and is generally regarded as the principal textbook on designing with geosynthetics. This textbook is an excellent reference book on geosynthetic functions, material properties, applications and design methods. Several other excellent reference sources include the books by Holtz *et al*. (1995), Ingold and Miller (1990) and Shukla (2002).

Journals devoted to geosynthetics include *Geotextiles and Geomembranes* (an official journal of the International Geosynthetics Society (IGS) published by Elsevier) and *Geosynthetics International* (an official journal of the IGS published by Thomas Telford). The Industrial Fabrics Association International annually publishes the *Geotechnical Fabrics Report (GFR)* specifier's guide, which is a directory of the property specifications of more than 500 geosynthetics from 50 international producers and is an excellent resource for designers.

International and national organizations setting and publishing testing standards include the European Committee for Standardization (Comité Européen de Normalisation, CEN) (2006), International Organization for Standardization (ISO) (2006), International Union of Laboratories and experts in Construction Materials, Systems and Structures (RILEM) (2006), Netherlands Normalisatie-instituut (NEN) (2006), Association Française de Normalisation (AFNOR) (2006), Deutches Institut für Normung (DIN) (2006), British Standards Institution (BSI) (2006), Ente Nazionale Italiano di Unificazione (UNI) (2006) and American Society of Testing and Materials (ASTM) (2006). Professional societies devoted to geosynthetics include the IGS and its associated chapters, and the Geo-Institute Committee on Geosynthetics of the American Society of Civil Engineers.

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3
The durability of geosynthetics

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3.1   Introduction

Durability is a major issue for all polymeric materials, including geosynthetics, when long design lifetimes are required. Geosynthetics used in critical applications have service lifetime requirements of 30 years to hundreds of years. In some cases, failure may be dramatic and result in high cost and even loss of life. Over the last few decades, lessons have been learned from case histories and considerable research. This chapter of the book will try to answer the question: 'How long will a particular geosynthetic last?' The complicated answer is largely dependent on the polymeric type and its specific formulation as well as its *in situ* exposed environment over time.

3.1.1   Common geosynthetics

Geosynthetics are formulated materials consisting of, at the minimum, the following.

1   The resin from which the name derives.
2   Carbon black or colorants,
3   Short-term processing stabilizers.
4   Long-term antioxidants.

If the formulation changes (particularly the additives), the predicted lifetime will also change. See Table 3.1 for the most common types of geosynthetics and their approximate weight formulations. A description of the commonly used geosynthetic polymers follows.

Polyethylene

Polyethylene (PE) is a common thermoplastic polymer used throughout the world. Its name originates from the monomer ethene used to create the polymer. It can be

Table 3.1 Types of commonly used geosynthetic resins and their approximate weight percentage formulations

Type	Resin (%)	Plasticizer (%)	Fillers (%)	Carbon black or pigment	Additives (%)
Polyethylene	95–98	0	0	2–3	0.25–1
Polypropylene (flexible)	85–98	0	0–13	2–4	0.25–2
Poly(vinyl chloride)	50–70	25–35	0–10	2–5	2–5
Poly(ethylene terephthalate)	98–99	0	0	0.5–1	0.5–1
Polyamide	98–99	0	0	0.5–1	0.5–1
Polystyrene	98–99	0	0	0	1–2

produced through radical polymerization, anionic polymerization and cationic polymerization. This is because ethene does not have any extraneous groups which influence the stability of the propagation head of the polymer. Each of these methods results in a different type of PE.

PE is classified into several different categories based mostly on its physical (mainly density) and mechanical properties. The mechanical properties of PE depend significantly on variables such as the extent and type of branching, the crystal structure and the molecular weight. The following resins are commonly used in geosynthetics and classified according to ASTM D883 (ASTM International, 2000) and ASTM F412 (ASTM International, 2001) by density.

1   High-density polyethylene (HDPE), greater than 0.940 g/cm^3
2   Medium -density polyethylene (MDPE), 0.940–0.926 g/cm^3
3   Linear low-density polyethylene (LLDPE), 0.925–0.919 g/cm^3
4   Low-density polyethylene (LDPE), 0.925–0.910 g/cm^3

High-density polyethylene
HDPE has a low degree of branching and thus stronger intermolecular forces and tensile strength. The lack of branching is ensured by an appropriate choice of catalyst (e.g. Ziegler–Natta catalysts) and reaction conditions.

Medium-density polyethylene
MDPE is a branched polyethylene having a slightly lower density than HDPE. It is the most commonly used polyethylene resin in geosynthetics. It is interesting to note that only after the addition of carbon black and the additive package does the compound cross into the density threshold into HDPE.

Linear low-density polyethylene
LLDPE is a substantially linear polymer, with significant numbers of short branches, commonly made by copolymerization of ethylene with longer-chain olefins. Depending on the crystallinity and molecular weight, a melting point and

glass transition may or may not be observable. The temperature at which these occur varies strongly with the type of PE.

Low-density polyethylene

LDPE has a high degree of branching, which means that the chains pack into the crystal structure as well. It has therefore less strong intermolecular forces as the instantaneous-dipole–induced-dipole attraction is less. This results in a lower tensile strength and increased ductility. LDPE is created by free-radical poly-merization.

Polypropylene

Polypropylene (PP) is a common thermoplastic used throughout geosynthetics because in large part of its cost-effectiveness. PP is created through polymerization of propylene gas. It is obtained from high-temperature cracking of petroleum hydrocarbons and propane. It is not surprising that PP and PE (known collectively as polyolefins, or simply olefins) have many of the same properties. However, they differ in the following respects.

1   PP has a lower density.
2   The service temperature of PP is higher.
3   PP is harder and more rigid.
4   PP is more resistant to environmental stress cracking.
5   PP is more susceptible to oxidation and chemical attack than PE is.

There are three basic structural stereostatic arrangements of PP. They are isotactic, atactic and syndiotactic. Commercially available PP is 95% isotactic and is exclusively used in geosynthetics.

Poly(vinyl chloride)

Poly(vinyl chloride) (PVC) is a widely used polymer. In terms of revenue generated, it is one of the most valuable products of the chemical industry. Globally, over 50% of PVC manufactured is used in construction for house siding, piping, etc. As a building material, PVC is inexpensive and easy to assemble. In recent years, PVC has been replacing traditional building materials such as wood and concrete. Despite appearing to be an ideal building material, concerns have been raised about the environmental and human health costs of PVC.

  PVC is produced from its monomer, vinyl chloride. PVC is a hard plastic that is made softer and more flexible by the addition of plasticizers, the most widely used being phthalates. When used as a geomembrane, plasticizer additions of 25–35% are common (Table 3.1).

Polyester

Polyester is a category of polymers or, more specifically, condensation polymers which contain the ester functional group in their main chain. Such compounds are formed by reaction of alcohols with acids via a chemical bonding known as an ester linkage. There are literally thousands of known esters which appear in many different forms. The chemical name of the polyester formed from the alcohol ethylene glycol and the acid terephthalic acid, or its derivative dimethyl terephthalate is poly(ethylene terephthalate) (PET). Although polyesters do exist in nature, polyesters generally refer to the large family of synthetic polymers.

Polyamide

A polyamide (PA) is a polymer containing monomers joined by peptide bonds. They can occur both naturally, examples being proteins such as wool and silk, and can be made artificially, examples being nylon and Kevlar. Nylon is the polymer sometimes used in geosynthetics.

   Production of the monomer is accomplished when an amide link is obtained from the condensation reaction of an amino group and a carboxylic acid or acid chloride group. A small molecule, usually water, ammonia or hydrogen chloride, is eliminated.

   The amino group and the carboxylic acid group can be on the same monomer, or the polymer can be constituted of two different bifunctional monomers, one with two amino groups, and the other with two carboxylic acid or acid chloride groups.

Polystyrene

Polystyrene (PS) is a polymer made from the monomer styrene, a liquid hydrocarbon that is commercially manufactured from petroleum. At room temperature, PS is normally a solid thermoplastic but can be melted at higher temperature for moulding or extrusion, then resolidified. Styrene is an aromatic monomer and PS is an aromatic polymer.

   PS was first manufactured by BASF in the 1930s and is used in numerous plastic products. The most common use of PS in geosynthetics is as expanded PS, which is a mixture of about 5% PS and 95% air. This is the lightweight material in which the voids filled with trapped air give expanded PS a low thermal conductivity. It is also used as insulation in building structures. PS for architectural and engineering applications can also be extruded into forms of standard cross-sections or into sheets with various patterns. Expanded PS used to contain chloroflurocarbons but other, more environmentally safe, blowing agents are now used.

   Table 3.1, from the book by Koerner (2005), illustrates the approximate formulations of commonly used geosynthetic polymers. Table 3.2, also from the

Table 3.2 Repeating units of polymers used in the manufacture of geosynthetics

Polymer	Repeating unit	Types of geosynthetic
Polyethylene	$\left[\begin{array}{c} H\ H \\ -C-C- \\ H\ H \end{array}\right]_n$	Geotextiles, geomembranes, geogrids, geopipe, geonets, geocomposites
Polypropylene	$\left[\begin{array}{c} H\ CH_3 \\ -C-C- \\ H\ \ H \end{array}\right]_n$	Geotextiles, geomembranes, geogrids, geocomposites
Poly(vinyl chloride)	$\left[\begin{array}{c} H\ Cl \\ -C-C- \\ H\ H \end{array}\right]_n$	Geomembranes, geocomposites, geopipe
Polyester [poly (ethylene tere-phthalate)]	$\left[O-R-O-\overset{O}{\underset{\parallel}{C}}-R'-\overset{O}{\underset{\parallel}{C}} \right]_n$	Geotextiles, geogrids
Polyamide (Nylon 6/6)	$\left[\overset{H}{\underset{\vert}{N}}-(CH_2)_6-\overset{H}{\underset{\vert}{N}}-\overset{O}{\underset{\parallel}{C}}-(CH_2)_4-\overset{O}{\underset{\parallel}{C}} \right]_n$	Geotextiles, geocomposites, geogrids
Polystyrene	$\left[\begin{array}{c} H\ H \\ -C-C- \\ H\ C \end{array}\right]_n$ with phenyl ring: $H-C$, $C-H$, $H-C$, $C-H$, $C-H$	Geocomposites, geofoam

book by Koerner (2005), shows the repeating molecular unit from which the resins generate their names and the types of polymer from which the geosynthetics are made.

3.1.2   Degradation

Under the right set of circumstances, all materials, including the polymers listed in the above tables, will degrade over time. Various degradation mechanisms affecting polymeric materials can act in isolation or synergistically. They are as follows.

In-isolation effects

1 *Ultraviolet (UV) light degradation* occurs only when the geosynthetic is exposed to UV light. Its intensity varies depending upon the location on the globe, atmosphere and time of year.
2 *Radiation degradation* is not a factor unless the polymer is exposed to radioactive materials of sufficiently high intensity to cause chain scission, e.g. high-level radioactive waste materials.
3 *Chemical degradation* can occur in all polymers and varies from water (least aggressive) to organic solvents (most aggressive).
4 *Hydrolysis degradation* is the primary degradation mechanism for polyesters and PAs. Technically, hydrolysis is a reaction with water. That is what happens when esters are hydrolysed by aqueous solutions of various pH values. Jailloux *et al.* (1992) suggested that the alkaline hydrolysis of esters actually involves reaction with hydroxide ions.
5 *Swelling* refers to a growth in bulk as a result of the uptake or adsorption of liquids.
6 *Extraction* refers to a pull-out or withdrawal of components by means of a non-equilibrium driving force such as heat, pressure, diffusion, dispersion or convection.
7 *Delamination r*efers to a splitting apart or separation into layers.
8 *Oxidative degradation* occurs in all polymers and is the major degradation mechanism in PE and PP (Comer *et al.*, 1998).
9 *Biological degradation* is generally not a factor unless biologically sensitive additives (such as low-molecular-weight plasticizers) are included in the polymer formulation.

Synergistic effects

1 *An elevated temperature* is an enabling variable for all the previously mentioned mechanisms. The higher the temperature, the more rapid is the degradation.
2 *Applied stresses* are a complicating factor which is site specific and should be appropriately modelled in the incubation process.
3 *Multiple and/or changing mechanisms over time* need to be considered. It is unlikely that any of the previously described degradation mechanisms are acting alone and in isolation from all others. When considering long service lifetimes of 100 years and beyond (Rollin, 2004), this is almost a certainty in most applications. It is, however, an extremely difficult situation to model owing to the unpredictability of future events and actions.

Each of these mechanisms will be discussed in the subsequent section of this chapter.

3.2   Mechanisms of degradation

This section describes various polymer degradation processes. Each process is discussed as if it were acting in isolation. This is not indicative of general field conditions. However, it is necessary to describe the isolated events before synergistic effects can be considered and discussed in the subsequent section.

3.2.1   Ultraviolet light degradation

As shown in Fig. 3.1, the spectrum of natural light is broken into two major regions (visible and UV) according to the wavelength of solar radiation. It is well established in the polymer literature that certain wavelengths within the UV portion are particularly degrading to polymeric materials. Van Zaten (1986) mentioned the following commonly used polymers and their most sensitive wavelengths, all of which are in the UV region and are noted on Fig. 3.1.

1   PE, most sensitive wavelength = 300 nm
2   PP, most sensitive wavelength = 370 nm
3   PVC, most sensitive wavelength = 312 nm
4   Polyester, most sensitive wavelength = 325 nm
5   PA, most sensitive wavelength = 320 nm
6   PS, most sensitive wavelength = 315 nm

Furthermore, the mechanism of degradation is well understood. The light with the most sensitive wavelength enters into the molecular structure of the polymer, liberating free radicals which cause bond scission in the primary bonding of the
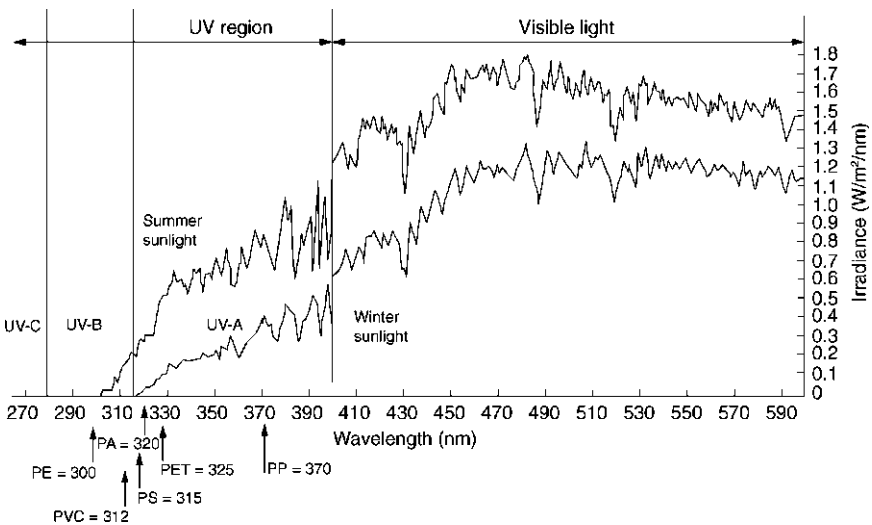
3.1 The wavelength spectra of visible and UV solar radiation.

polymer's backbone. This mechanism, in direct proportion to the intensity, causes a reduction in mechanical properties until eventually the polymer becomes brittle and cracks to unacceptable levels.

The above type of degradation is greatly reduced by the use of carbon black or chemically based light stabilizers. Carbon black is a finely dispersed powder of approximately micrometre size which acts as a blocking (or screening) agent to prevent the UV light from entering into the polymer structure. It also absorbs some of the energy. Its effectiveness decreases uniformly with time of exposure so that the amount and dispersion of the carbon black are important (Apse, 1989). The maximum amount, however, is limited to the amount that interferes with the growth and strength of the polymer structure. Hindered amine light stabilizers (HALS) are chemicals added to the polymer compound which react with the free radicals liberated by the UV light, preventing the propagation of degradation. When such additives are consumed, however, continued UV exposure will cause rapid degradation of the polymer. A combination of carbon black and chemical absorbers has been shown to be very effective in avoiding UV-induced degradation of polymers (Grassie and Scott, 1985).

For geosynthetic applications, a soil backfill or other covering eliminates the problem of UV degradation entirely. Only exposed geosynthetics are subjected to UV degradation and as little as 15 cm of soil cover is sufficient to prevent its occurrence. Obviously, this cover soil must be placed in a timely fashion which can be achieved in all applications except for the following.

1 Surface impoundments above the liquid level and along their horizontal run-out length.
2 Canal liners above the liquid level and along their horizontal run-out length.
3 Covers of surface impoundments, i.e. floating covers.
4 Landfill liners on side slopes which have had their surfaces exposed by erosion of cover soil and are inaccessible.
5 Exposed geomembranes on masonry, concrete and roller-compacted dams.

3.2.2   Radiation degradation

There are a number of reviews on the effects of radiation on polymer properties (Charlesby, 1960; Phillips, 1988). An extremely brief summary will be given here. The effects of γ-rays, neutrons and β-rays are essentially equivalent when their different penetrating powers are considered. β-rays (electrons) penetrate about a millimetre into a polymer, whereas γ-rays and neutrons penetrate much further. α-rays (helium nuclei) penetrate only micrometres and hence are only involved with very-near-surface damage.

The basic mechanical short-term properties of a typical polymer start to change at a total radiation dose of between 10^6 and 10^7 rad (Phillips, 1988). A rad is equivalent to 100 erg of absorbed energy per gram of material. For reference

purposes, the dose of radiation lethal to a human is about 100–200 rad. Therefore it would appear that, if a geosynthetic is containing low-level nuclear waste of even lower radiation than the lethal human dose, the time before significant damage occurs to its short-term mechanical properties will be quite long. Other, more subtle changes may occur. For example, even very small amounts of local surface damage in a semicrystalline geosynthetic might cause reduction in the stress crack resistance of the material. The effects of radiation on the additives may be a more severe problem than the effect on the polymer itself. It is possible, that after a certain irradiation, the material will be more susceptible to other degradation processes.

While no test protocol exists for evaluation, some form of incubation test method can be used with suitable modifications. Whyatt and Fansworth (1990) have evaluated a number of different geomembranes in simulated short-term tests in a high-pH (about 14 wt% NaOH) inorganic solution at 90 °C and subjected them to radiation dose of up to 39×10^6 rad. It was found that only polyolefin geomembranes were unaffected by the radiation. Furthermore, the radiation did not have a significant effect on other chemical degradation rates.

3.2.3   Chemical degradation

The reaction of various geosynthetics to chemicals has probably been studied more than any other degradation mechanism. Most of the work is laboratory orientated via simple immersion tests but the body of knowledge is so great that a reasonable confidence level can be associated with manufacturers' listings and recommendations.

Polymer chains are linked together by weak interchain interactions. In order to avoid alteration, interactions between the chains must be stronger than between the solvent and the polymer. Such polymer–solvent interactions are generally based on polarity. The higher the polarity of the solvent and polymer, the stronger are the possible interactions. This explains why polymers with low polarity such as PE and PP are resistant to a vast array of chemicals. When solvents penetrate polymers, they begin to break the interaction between polymer chains, increasing the distance between them and reducing their attraction, which increases their mobility. This typically leads to swell and softening of the material, opening it up for further attack.

Neat chemicals yield insight into possible chemical interaction but they are far from real-world performance. Complex waste streams such as leachate need to be evaluated and are usually addressed on a site-specific basis. For this reason, the US Environmental Protection Agency (1982, 1984, 1987) developed procedures which are now embodied in ASTM D5322 (ASTM International, 1998b). In this method, samples of the candidate geosynthetic are exposed at 23 and 50 °C and removed at 30, 60, 90 and 120 days. Various physical and mechanical tests are performed and then compared with the unexposed material, e.g. ASTM D5747

(ASTM International, 1995) for geomembranes. A percentage change in this behaviour is determined. When plotted for the various exposure times, trends can be established and a decision made as to the nature and degree of chemical degradation.

Depending on the type of leachate *vis-à-vis* the polymeric compound from which the geosynthetic is made, a number of variations may occur.

1 No change may occur, which indicates that the material is resistant to the leachate at least for the time periods and temperature evaluated.
2 Swelling of the geosynthetic may occur, which in itself may not be significant. Many polymers can accommodate liquid in their amorphous regions without a sacrifice of physical or mechanical properties. Swelling, however, is often the first stage of subsequent degradation and small losses in modulus and strength may occur. The effect is often reversible when the liquid is removed.
3 A nominal, but statistically significant, change in a physical or mechanical property, of course, signifies some type of chemical reaction. The variations are enormous. Quite often the elongation at break in a tensile test will be the first property to show signs of change. It will first occur with the 50 °C incubation data, since this can be considered to be an accelerated temperature test over the 23 °C incubation data.
5 A large change in a physical or mechanical property signifies an unacceptable performance of the material. Limits of acceptability are, however, very subjective. O'Toole (1985–1986), Little (1985) and Koerner *et al.* (1990) suggested recommendations and there are also several expert computer codes available to aid in the decision.

3.2.4 Hydrolysis degradation

Polyester (PET) fibres have been extensively studied to understand the effects of various chemicals with regard to hydrolysis (Risseeuw and Schmidt, 1990; Schmidt *et al.*, 1994; Salman *et al.*, 1997). Polyester is a polymer where the individual units are held together by ester linkages. In condensation polymerization, when the monomers join together a small molecule is lost. This is different from addition polymerization which produces polymers such as PE in which nothing is lost when the monomers join together.

Hydrolysis is a chemical reaction in which a substance reacts with water and becomes a changed substance. This involves the ionization of the water molecule, as well as splitting of the compound hydrolysed. The chemical process in which scission of a chemical bond occurs via reaction with water is accelerated by extreme acidic or alkali environments.

The polyester-chemical-bond polymers are subject to hydrolysis, thereby producing alcohol and acid end groups. Hydrolysis is a reversible reaction, meaning that the alcohol and acid groups can react with each other to produce a polyester

bond and water as a by-product. In practice, however, a degraded polyester fibre will never fully reconstruct back to its original integrity if left in its *in situ* environment.

Factors affecting the rate and amount of hydrolysis depend upon the following.

1   Textile geometry and structure (Halse *et al.*, 1987a, 1987b).
2   Yarn and/or filament cross-section (Collins *et al.*, 1991).
3   Heat setting temperature (Solbrig and Obendorf, 1991).
4   Additives in the fibre (Sanders and Zeronian, 1982).
5   Presence of co-monomers (McIntyre, 1985).
6   Applied stress (Rahman and Alfaro, 2004).

A study sponsored by the US Federal Highway Administration found that polyester geosynthetics are sensitive to hydrolytic degradation at elevated pH levels (Elias, 1998). Elias found that hydrolytic degradation of polyester increased 2.4 times when pH values increased from 7 to 10. Polyester deterioration via hydrolysis will be catalysed by either acids or bases. The reaction rate is also sensitive to temperature. Polyester can be made hydrolysis resistant by increasing its molecular weight above a minimum number molecular weight M_n of 25 000 (Geosynthetic Research Institute, 1999) and reducing the number of carboxyl end groups below a threshold level of 30 (Geosynthetic Research Institute, 1998).

3.2.5   Swelling

One indication of a geosynthetic's durability is the amount of swelling that occurs owing to liquid absorption. It should be emphasized that swelling *per se* does not necessarily mean chain scission nor a failed system. It is, however, slightly disconcerting and usually results in changes in physical and mechanical properties, at least on a temporary basis.

The test for water absorption, which can be modified for any liquid, has been given in ASTM D570 (ASTM International, 1998a). The test is directed at a quantitative determination of the amount of water absorbed, but it is also used as a quality control test on the uniformity of the finished product. The test procedure cautions that the liquid absorption may be significantly different through the edge or through the surface, particularly with laminated products. (This fact alone suggests that in seaming of laminated geomembranes, the upper overlap must be protected against moisture uptake.) Test specimens of 75 mm by 25 mm are used and immersed in a number of possible ways.

1   Under constant immersion for 2 h, 24 h or 2 weeks in 23 °C water.
2   Under cyclic (repeated) immersion.
3   Under constant immersion for 0.5 h or 2 h in 50 °C water.
4   Under constant immersion for 0.5 h or 2 h in boiling water.

The resulting test data are reported as the percentage increase in weight using

deionized and distilled water. Some typical values for commonly used geomembranes are as follows (Haxo *et al.*, 1985).

1 PE, negligible.
2 PP, negligible.
3 PVC, 3–4%.
4 PET, 0.5–1%.
5 PA, 0.5–1%.
6 Non-expanded PS, 0.2– 0.7%.

Swelling due to other liquids has been mentioned in the reference cited. It is both liquid and condition dependent.

3.2.6   Extraction

Some polymers exhibit degradation by the long-term extraction of one or more components of the formulation from the polymeric material. These are usually polymers which have been compounded with the use of plasticizers and/or fillers. The as-formulated and compounded mixture of such polymers is very intricate and the bonding mechanic is very complex. When extraction of plasticizers does occur, a sticky surface results with the remaining structure showing signs of increased modulus and strength, and a lowering of the elongation at failure, i.e. the material becomes progressively brittle (Doyle and Baker, 1989). The long-term behaviour, however, is unknown. It is also possible that antidegradation components within the polymer may be extracted and leach out to the surface. This might indicate that the remaining polymer is somewhat more sensitive to long-term degradation.

Over time, plasticizers can migrate from PVC by contact with air, liquid or adsorbent solids. This can result in reduced flexibility, shrinkage and even cracking. The plasticizers used in PVC are either polymers or monomers. Monomeric plasticizers are more commonly used because of their cost-effectiveness; see Miller *et al.* (1991), Hammon *et al.* (1993) and Giroud and Tisinger (1994) for more detail in this regard. To guard against a significant amount of plasticizer migration, a minimum molecular weight of the plasticizer is generally specified (Stark *et al.*, 2005). The plasticizer mobility, commonly related to molecular weight, is one of the main factors in the diffusion of plasticizer out of the polymer structure. Nass and Heiberger (1986), Kays (1988) and Wilson (1995) suggested that linearity, polymer morphology, polarity and relative amount of the plasticizer may also be factors that control plasticizer retention. Scuero (1990) and Cazzuffi (1998) showed that there exists many PVC formulations, with quite different durability characteristics.

3.2.7   Delamination

For geosynthetics which are manufactured in individual layers, or plies,

delamination is a possibility. Calendering or spreading the coating are the usual production methods. Delamination is observed when liquid enters into the edge of the unprotected material and is drawn into the interface by capillary tension. This can occur between plies, within reinforcing scrim or between the coating of a fabric substrate. When it occurs, the individual components are separated and composite action is lost. This type of wicking action has been problematic in the past but current manufacturing methods and proper construction quality control and construction quality assurance in field operations have almost eliminated the situation.

3.2.8   Oxidative degradation

Whenever a free radical is created, e.g. on a carbon atom in the PE chain, oxygen can create degradation. The oxygen combines with the free radial to form a hydroperoxy radical, which is passed around within the molecular structure. It eventually reacts with another polymer chain creating a new free radical causing chain scission. The reaction generally accelerates once it is initiated.

Antioxidants are added to the compound to scavenge these free radicals in order to halt, or at least to interfere with, the process. These additives, or stabilizers, are specific to each type of resin. This area is quite advanced with all resin manufacturers being involved in a meaningful and positive way. The specific antioxidants are usually proprietary. Removal of oxygen from the geosynthetic's surface, of course, eliminates the concern. Thus, once placed and covered with waste, or liquid, degradation by oxidation is greatly retarded but generally not eliminated. Conversely, exposed material or those covered by non-saturated soil will always be susceptible to the mechanism.

Oxidation as it is related to olefins can further be thought of in distinct lifetime stages (Müeller and Jacob, 2003), as shown in Fig. 3.2.
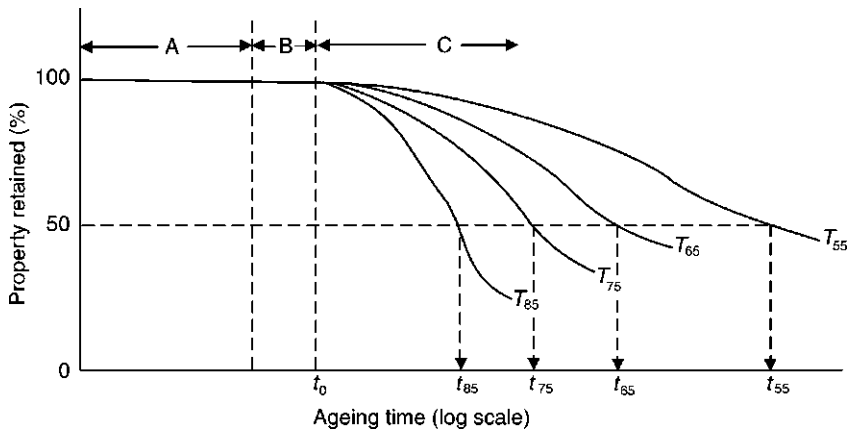
3.2 Three conceptual stages in the chemical ageing of polyolefin geomembranes: A, antioxidant depletion time; B, induction time; C, 50% property degradation time (the half-life).

Stage A is called the antioxidant time. In this regard, the purposes of antioxidants are, firstly, to prevent polymer degradation during processing and, secondly, to prevent oxidation reactions from taking place during service life. Obviously, there can only be a given amount of antioxidants in any formulation. Once the antioxidants are completely depleted, additional oxygen will begin to attack the polymer chains, leading to subsequent stages as shown in Fig. 3.2. The duration of the antioxidant depletion stage depends on both the type and the amount of antioxidants.

The depletion of antioxidants is the consequence of two processes.

1   Chemical reactions with the oxygen diffusing into the geomembrane.
2   Physical loss of antioxidants from the geomembrane.

The chemical process involves two main functions: the scavenging of free radicals converting them into stable molecules, and the reaction with unstable hydroperoxide (ROOH), forming a more stable substance. Regarding physical loss, the process involves the distribution of antioxidants in the geomembrane and their volatility and extractability.

Hence, the rate of depletion of antioxidants is related to the type and amount of antioxidants, the service temperature and the nature of the site specific environment. See Hsuan and Koerner (1998) for additional details.

Stage B is called the induction time. It is relatively short, since in a pure polyolefin resin, i.e. one without carbon black and antioxidants, oxidation occurs extremely slowly at the beginning, often at an immeasurable rate. Eventually, oxidation occurs more rapidly. The reaction eventually decelerates and once again becomes very slow. This progression is illustrated by the S-shaped curve of Fig. 3.3(a). The initial portion of the curve (before measurable degradation takes place) is called the induction period, or induction time, of the polymer. In the induction period, the polymer reacts with oxygen, forming hydroperoxide (ROOH), according to

$$RH \rightarrow R \bullet + H \bullet \qquad [3.1]$$

(aided by energy or catalyst residues in the polymer),

$$R \bullet + O_2 \rightarrow ROO \bullet \qquad [3.2]$$
$$ROO \bullet + RH \rightarrow ROOH + R \bullet \qquad [3.3]$$
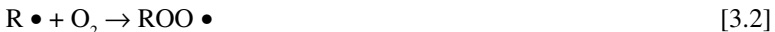
In the above equations, RH represents the polyethylene polymer chains and the symbol $\bullet$ represents free radicals, which are highly reactive molecules. However, the amount of ROOH in this stage is very small and the hydroperoxide does not further decompose into other free radicals which inhibits the onset of the acceleration stage.

In a stabilized polymer such as a polymer with antioxidants, the accelerated oxidation stage takes an even longer time to be reached. The antioxidants create an additional depletion time stage prior to the onset of the induction time, as shown in Fig. 3.3(b).
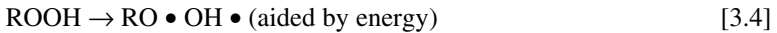
(a)

Ageing time
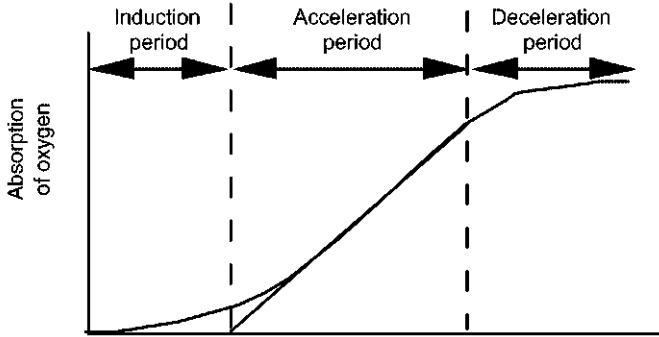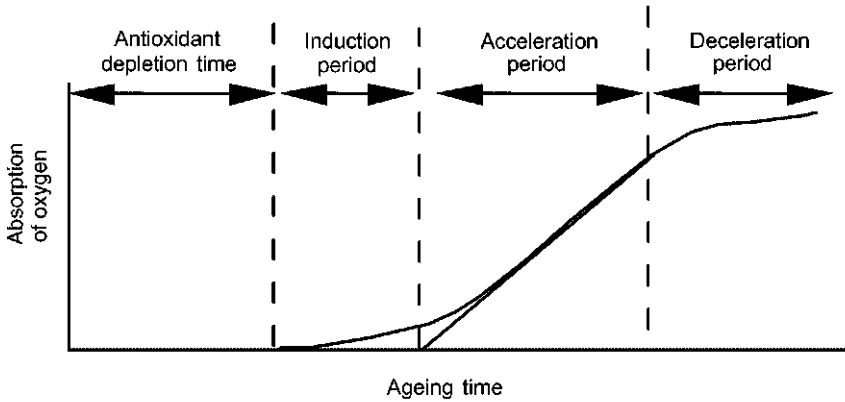
(b)

3.3 Curves illustrating various stages of oxidation: (a) unstabilized polyethylene; (b) stabilized polyethylene.

In *Stage C*, the physical and mechanical properties begin to degrade as oxidation continues and additional ROOH molecules are being formed. Once the concentration of ROOH reaches a critical level, decomposition of ROOH begins, leading to a substantial increase in the amount of free radicals, according to

$$ROOH \rightarrow RO \bullet OH \bullet \text{ (aided by energy)} \qquad [3.4]$$
$$RO \bullet + RH \rightarrow ROOH + R \bullet \qquad [3.5]$$
$$OH \bullet + RH \rightarrow H_2O + R \bullet \qquad [3.6]$$

The additional free radicals rapidly attack other polymer chains, resulting in an accelerated chain reaction, signifying the end of the induction period (Rapoport and Zaikov, 1986). This indicates that the concentration of ROOH has a critical control on the duration of the induction period.

The oxidation produces a substantial amount of free radical polymer chains (R•), called alkyl radicals, which can proceed to further reactions, leading to either cross-linking or chain scission in the polymer. As the degradation of polymer continues, the physical and mechanical properties of the polymer start to change. The most noticeable change in physical properties is in the melt index, since it relates to the molecular weight of the polymer. As for the mechanical properties, both tensile break stress (strength) and break strain (elongation) decrease. Ultimately, the degradation becomes so severe that all tensile properties start to change (tear, puncture, burst, etc.) and the engineering performance is jeopardized. This signifies the end of the so-called 'service life' of the geomembrane.

Although quite arbitrary, the limit of service life of polymeric materials is often selected as a 50% reduction in a specific design property. This is commonly referred to as the half-lifetime, or simply the 'half-life'. It should be noted that even, at half-life, the material still exists and can function, albeit at a decreased performance level with a factor of safety lower than the initial design value.

3.2.9 Biological degradation

Within the various plant forms of biological life, i.e. bacteria, antinomycetes, fungi, and algae, polymer degradation is essentially impossible owing to the high molecular weight of the common resins used in geomembranes. In order for such degradation to occur, the chain ends must be accessible and this is highly unlikely for molecular weights greater than 1000, let alone 10 000–30 000, which is common for geomembrane resins. Biological degradation might be possible for plasticizers or additives compounded with the resin, but information is not authoritative on this subject.

Within the higher forms of biological life, i.e. protozoa, spiders, insects, moles, rats and small mammals, polymers do not contain food and thus are unlikely to be consumed. It is possible, however, that an animal may try to penetrate the synthetic for access to the opposite side. In this case, hardness of the predator's teeth enamel versus the geomembrane's hardness is the key comparison. While such events are possible, authoritative information is not known to the present authors.

Verification of biological resistance is confirmed by a soil, sewage or sludge burial test. It is usually carried out for long exposure times, at a nearly neutral pH and at an elevated temperature. The test specimens are periodically removed from the soil and tested for changes in properties. The extent of the degradation is also examined by way of surface microscopy and various fingerprinting techniques.

3.3   Synergistic effects

While not degradation mechanisms within, or of, themselves, there are several phenomena which can readily work in conjunction with the previously discussed items. They generally have the effect of accelerating the specific degradation

process and thus are called 'synergistic effects'. At the outset it should be noted, however, that the quantification of these effects is very complicated and the database is very weak in this regard.

3.3.1   Elevated temperatures

Whenever the temperature at the surface or within the geosynthetic is increased, the material expands, chains deform, the mobility of the polymer (and of its other ingredients) is increased, and degradation is usually accelerated. All can result in internal chain reorganization in the presence of a driving force. The stressed chain segments can move and reorganize themselves in order to reach a more stable state. Such movements may lead to morphological modifications which can lead to material degradation. Of the different degradation mechanisms mentioned earlier, this is the case for all of them with the possible exception of biological degradation, which was seen to be of negligible significance. Clearly, elevated temperatures accelerate UV degradation; this phenomenon is arguably the most important and has the largest database. Thus extreme conservatism is usually taken when testing for UV degradation. As mentioned earlier, chemical resistance incubation is usually carried out at an elevated temperature of 50 °C for comparison with the 23 °C 'standard' temperature. Invariably, the higher temperature produces results having greater changes than the lower temperature does. There is an upper limit for such temperature testing, however, and that value is based upon polymer modification not representative of realistic behaviour. Its value is undoubtedly resin dependent but largely unknown.

For geosynthetics placed in the field, high temperatures can generally be avoided by covering the geosynthetics with soil, liquid or another material. Thus, the buried environment greatly reduces temperatures in most synthetic applications. Notable exceptions are surface impoundment and canal liners (above the liquid surface), floating covers and exposed dam waterproofing. For all these cases, simulated testing is absolutely necessary (Sangam and Rowe, 2002).

For an accelerated simulation of direct sunlight using a laboratory weatherometer, one usually considers a worst-case situation which is the solar maximum condition. This condition consists of global noon sunlight, on the summer solstice, at normal incidence. It should be recognized that UV-A range is the target spectrum for a laboratory device to simulate the naturally occurring phenomenon (Hsuan and Koerner, 1993; Suits and Hsuan, 2001).

The xenon arc weatherometer [ASTM G155 (ASTM International, 2005)] was introduced in Germany in 1954. There are two important features: the type of filters and the irradiance setting. Using a quartz inner and borosilicate outer filter results in excessive low-frequency wavelength degradation. The more common borosilicate inner and borosilicate outer filters shows a good correlation with solar maximum conditions, although there is an excess of energy below 300 mm wavelength. Irradiance settings are important adjustments in shifting the response

although they do not eliminate the portion of the spectrum below 300 nm frequency. Nevertheless, the xenon arc weatherometer is a commonly used method for exposed lifetime prediction of all types of geosynthetic.

UV fluorescent lamps (ASTM G154 (ASTM International, 2004b)) are an alternative type of accelerated laboratory test device which became available in the early 1970s. They reproduce the UV portion of the sunlight spectrum but not the full spectrum as in xenon arc weatherometers. Earlier FS-40 and UV-C-313 lamps gave reasonable short wavelength output in comparison with solar maximum. The UV-A-340 lamp was introduced in 1987 and its response is seen to reproduce UV light quite well. This device (as well as other types of weatherometer) can handle elevated temperature and programmed moisture on the test specimens. Such investigations are routinely being conducted around the world and are commonly specified.

3.3.2   Applied stresses

Invariably, the testing for geosynthetic degradation is performed on unstressed laboratory samples. Yet, at the very least, the geosynthetics will have compressive stresses imposed and, quite possibly, tensile stresses as well. What these stresses do to the degradation of the geosynthetics in comparison with testing unstressed samples is largely unknown. The reason for this lack of data is obvious. The cost of experimentation at elevated temperatures is very high in itself and to stress the material in some simulated form of biaxial or triaxial stress would generally be cost prohibitive. Yet, some experimentation with stressed geosynthetics is being initiated, most of which are trying to identify the severity of the effect.

Environmental stress cracking consists of a brittle failure of stressed samples in the presence of a wetting agent. It is of concern when geosynthetics are made of HDPE. This type of failure differs from ductile failure (creep) in that, despite the stress applied on a fairly large area, the deformation only takes place within a thin cross-section and ultimately leads to complete brittle rupture of the material. In addition, the stress level involved in this mechanism is generally less than half the yield stress of the material (Hsuan, 2000). With the advent of ASTM D5397 (American Society for Materials and Testing, 1999) this problem has largely been eliminated from our marketplace. The GRI-GM13 specification (Geosynthetic Research Institute, 1997) requires a 300 h failure time, which requires a quality resin combined with a good additive package.

3.3.3 Multiple and/or changing mechanisms over time

Long exposure results in a multiplicity of effects such as those due to UV, extraction and oxidation, which can result in synergistic effects beyond the previously discussed phenomenon taken individually. For materials as inert as PE, for example, exposure for years at ambient temperature shows no indication of any

change in properties. For other polymers, some changes in surface texture or even in macroscropic properties might occur, but their influence on the geosynthetic's behaviour is not clear.

The major authoritative database on long-term ageing is available from Matrecon, Inc. (1988), but the steady development of new polymers and compounds makes the situation elusive, to say the least. It should be mentioned that a few landfill owners are beginning to place geosynthetic samples (coupons) in retrievable locations for annual exhuming and evaluation. Such studies will eventually be helpful in assessing actual degradation and ageing although the coupons are rarely, if ever, in a stressed condition.

3.4   Accelerated testing methods

Clearly, the long time frames involved in evaluating individual degradation mechanisms at field-related temperatures, compounded by the synergistic effects just mentioned, are not providing answers regarding geosynthetic durability behaviour fast enough for the long-term decision-making processes of today. Thus accelerated testing, by high stress, elevated temperature and/or aggressive liquids, is very compelling. Before reviewing these procedures, however, it must be clearly recognized that one is assuming that the high stress, elevated temperature or aggressive liquids used actually simulates extended lifetimes – an assumption which is not readily substantiated. Thus it might be that the test procedures to be described here actually form lower-bound conclusions in predicting degradation, i.e. the results may be minimum values but that is not known with any degree of certainty.

3.4.1   Stress limit testing

Focusing almost exclusively on HDPE pipe for natural gas transmission, the Gas Research Institute, the Plastic Pipe Institute and the American Gas Association are all very active in various aspects of plastic pipe research and development. The three above-mentioned organizations, together with Battelle Columbus Laboratories sponsor the Plastic Fuel Gas Symposia which are held on a biennial basis and the resulting *Proceedings* contain many interesting papers. Stress limit testing in the plastic pipe area has proceeded to a point where there are generally accepted testing methods and standards. ASTM D1598 (ASTM International, 2002) describes a standard experimental procedure, and ASTM D2837 (ASTM International, 2004a) gives guidance on the interpretation of the results of the ASTM D1598 test method.

In ASTM D1598 (ASTM International, 2002), long pieces of unnotched pipe are sealed, capped and placed in a constant-temperature environment. Room temperature of 23 °C is usually used. The pipes are placed under various internal pressures which mobilize different values of hoop stress in the pipe walls, and the

pipes are monitored until failure occurs. This is indicated by a sudden loss in pressure. Then the values of hoop stress are plotted versus failure times on a log–log scale. If the plot is reasonably linear, a straight line is extrapolated to the desired, or design, lifetime which is often 10^5 h or 11.4 years. The stress of this failure time reduced by an appropriate factor is called the hydrostatic design basis stress. While of interest for pipelines, the stress state of planar geosynthetics is essentially unknown and is extremely difficult to model. Thus, the technique is not of direct value for synthetic design. It leads, however, to the next method.

3.4.2   Rate process method for pipes

Research at the Gas Institute in Holland (Wolters, 1987) uses the method of pipe ageing that is most prevalent in Europe. It is also an International Standards Organization (ISO) tentative standard currently in committee. Note that other plastic pipe research institutes also are involved in this type of research. The experiments are again performed using sections of unnotched pipe which are tightly capped, but now they are placed in various elevated-temperature environments. So as to accelerate the process, elevated-temperature baths up to 80 °C are used. Different pressures are put in the pipes at each selected temperature so that known hoop stress occurs in the pipe walls. The pipes are monitored until failure occurs, resulting in sudden loss in pressure. Two distinct types of failure are found: ductile and brittle. The failure times corresponding to each applied pressure are recorded. A response curve is presented by plotting hoop stress against failure time on a log–log scale.

The rate process method is then used to predict a failure curve at some temperature other than those tested, i.e. at a lower (field-related) temperature than was evaluated in the high-temperature tests. This method is based on an absolute reaction rate theory as developed by Tobolsky and Eyring (1943) for the viscoelastic phenomenon. Coleman (1956) has applied it to explain the failure of polymeric fibres as used in geotextiles and geogrids. The relationship between failure time and stress is expressed in the following form:

$$\log t_f = A_0 T^{-1} + A_1 T^{-1} \sigma \qquad\qquad [3.7]$$

where

t_f = time to failure
T = temperature
σ = tensile stress on the fibre
A_0, A_1 = constants

Bragaw (1983) has revised the above model on polymeric fibres and found three additional equations which yield reasonable correlation to the failure data of HDPE pipe. These three equations are

$$\log t_{\mathrm{f}} = A_0 + A_1 T^{-1} + A_2 T^{-1} P \qquad [3.8]$$

$$\log t_{\mathrm{f}} = A_0 + A_1 T^{-1} + A_2 \log P \qquad [3.9]$$

$$\log t_{\mathrm{f}} = A_0 + A_1 T^{-1} + A_2 T^{-1} \log P \qquad [3.10]$$

where

P = internal pipe pressure proportional to the hoop stress in the pipe

The application of the rate process method requires a minimum of two experimental failure curves at different elevated temperatures well above 40 °C. The equation which yields the best correlation to these curves is then used in the prediction procedure for a response curve at a field-related temperature, e.g. from 10 to 25 °C. Two separate extrapolations are required: one for the ductile response and one for the brittle response. Three representative points are chosen on the ductile regions of the two experimental curves. One curve will be selected for two points, and the other for the remaining point. These data are substituted into the chosen equation, i.e. Equation [3.7], [3.8] or [3.9] to obtain the prediction equation for the ductile response of the curve at the desired (lower) temperature. The process is now repeated for the predicted brittle response curve at the same desired temperature. The intersection of these two lines defines the transition time.

3.4.3   Rate process method for geomembranes

A similar rate process method to that just described for HDPE pipes can be applied to HDPE geomembranes. The major difference is the method of stressing the material. The geomembrane tests are performed using a notched constant-load test which follows ASTM D5397 (ASTM International, 1999). In this test, dumbbell-shaped specimens are taken from the geomembrane sheet. A notch is introduced on one of the surfaces, the notch depth being 20% of the thickness of the sheet. The full description of the notching process has been described by Halse *et al.* (1990). Tensile loads varying from 30 to 70% of the yield stress of the sheet are applied to the notched specimens. The tests are performed in constant-elevated-temperature environments (usually from 40 to 80 °C) and in a surface-active wetting agent. In general, 10% Igepal and 90% tap water are used. The data are presented by plotting percentage yield stress against failure time on a log–log scale. Distinct ductile and brittle regions can be seen, together with a clearly defined transition time (Halse *et al.*, 1990).

3.4.4   Elevated-temperature and Arrhenius modelling

Using experimental chambers as shown in Fig. 3.4(a) and Fig. 3.4(b), Mitchell and Spanner (1985) have superimposed a compressive stress, chemical exposure, elevated temperature and long testing time onto a single experimental device. The Geosynthetic Institute has extended their work evaluating HDPE geomembranes

(a)

(b)
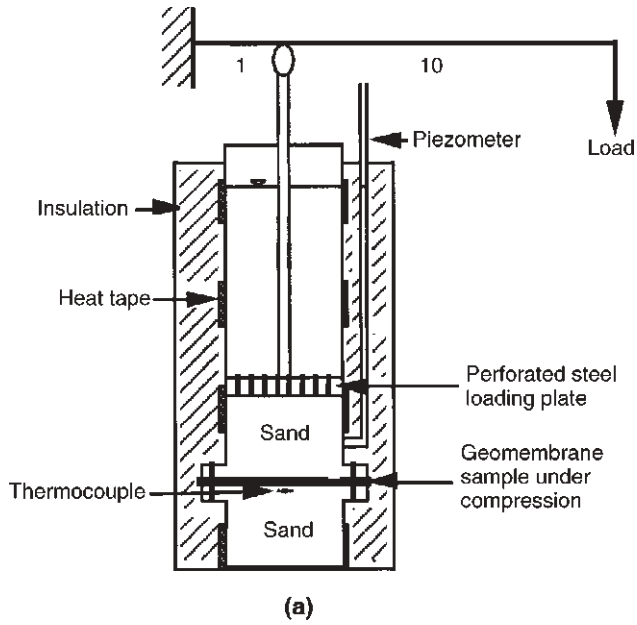
3.4 (a) Cross-section of the experimental chamber; (b) photograph of multiple cells maintained at various constant temperatures.

at 85, 75, 65 and 55 °C. At the end of the arbitrarily designated test period, the geomembrane samples are removed. Mechanical tests and chemical analyses are then performed on these incubated samples to monitor whether any changes in the various properties of the geomembrane occurred. The mechanical tests include the following.

1   Tensile strength and elongation.
2   Yield strength and elongation.
3   Stress cracking behaviour.

The chemical analysis tests include the following.

1   Differential scanning calorimetry, for measuring the crystallinity and oxidation induction time.
2   Infrared spectrometry, for measuring the concentration of carbonyl groups.
3   Gel permeation chromatography, for measuring the molecular weight and molecular weight distribution

If there are changes in any of the above properties, e.g. in the concentration of the carbonyl group, the reaction rate K is obtained for each experimental test temperature T. These values were now used with the Arrhenius equation, which is as follows (American National Standards Institute, 1986):

$$K = \exp\left(-\frac{E}{RT}\right) \qquad [3.11]$$

where

K = reaction rate for the process considered
A = constant for the process considered
E = reaction activation energy for the process considered
T = temperature (K = °C + 273)
R = gas constant (=8.314 J/mol K)

By plotting ln K against 1/T, a straight line is obtained. The slope of this line is E/R for the particular property change being monitored. The constant A can also be identified but it drops out of the equation when comparing the responses at two different temperatures.

We can now extrapolate graphically to a lower site-specific temperature. The essential equation for the extrapolation is

$$\frac{r_{T_{\text{test}}}}{r_{T_{\text{site}}}} = \exp\left[-\frac{E_{\text{act}}}{R}\left(\frac{1}{T_{\text{test}}} - \frac{1}{T_{\text{site}}}\right)\right] \qquad [3.12]$$

where

E_{act}/R = slope of Arrhenius plot.
T_{test} = incubated (high) temperature
T_{site} = site-specific (lower) temperature

Using experimental data from Martin and Gardner (1983) for the half-life of the tensile strength of a polybutylene terephthalate plastic, the E_{act}/R value is –12 800 K. The estimated life, extrapolating from the 93 °C actual incubation temperature (which took 300 h to complete) to a site-specific temperature of 20 °C can be solved as follows.

After converting from degrees Celsius to Kelvin,

$$\frac{r_{93\,°C}}{r_{20\,°C}} = \exp\left[-\frac{E_{act}}{R}\left(\frac{1}{93+273} - \frac{1}{20+273} \right)\right]$$

$$= \left[-12\,800 \left(\frac{1}{366} - \frac{1}{293} \right)\right]$$

$$= 6083 \qquad\qquad\qquad\qquad\qquad\qquad [3.13]$$

If the 93 °C reaction takes 300 h to complete, the equivalent 20 °C reaction would take

$$
\begin{aligned}
r_{20\,°C} \; &= \; 6083\,(300) \\
&= \; 1\,825\,000 \text{ h} \\
&= \; 208 \text{ years}
\end{aligned}
$$

Thus, the predicted time for this particular polymer to reach 50% of its original strength at 20 °C is approximately 200 years, its predicted lifetime for Stage C.

Table 3.3 takes the bold step of superimposing lifetime prediction from the three previously discussed stages and makes use of data from Viebke *et al*. (1994) and Martin and Gardner (1983) and much from the Geosynthetic Institute. The table also shows that temperatures higher than 20 °C will cause the lifetime to decrease exponentially. At 40 °C, the predicted lifetime of the same covered geomembrane would be approximately 80% less than at 20 °C. *In situ* temperatures of landfill liners and covers (for both dry and wet landfills) is an ongoing research project at the Geosynthetic Insitute. Koerner and Koerner (2005) gave recent data from facilities that have been monitored for over 13 years.

3.5   Summary and conclusion

This chapter on durability of geosynthetics has attempted to give insight into the long-term performance of these polymeric materials by itemizing those mechanisms that can degrade the resin and/or compound from which they are made. It presents various degradation mechanisms, taken individually, and then describes possible synergistic effects induced by anticipated field conditions. These effects greatly complicate the situation.

Long-term laboratory tests under simulated field conditions are absolutely essential for the future development and improvement of geosynthetics in this

Table 3.3 Lifetime prediction of a backfilled HDPE geomembrane as a function of *in situ* service temperature[a]

| In-service temperature (°C) | Stage A (years) | | Stage B (years) | Stage C (years) | | | Total prediction[b] (years) |
	Standard oxidation induction time	High-pressure oxidation induction time		Viebke *et al.* (1994)	Martin and Gardner (1983)	Geosynthetic Institute data	
20	200	215	30	740	208	8	555
25	135	144	25	441	100	7	348
30	95	98	20	259	49	6	221
35	65	67	15	154	25	5	142
40	45	47	10	93	13	4	93

[a]Exposed geomembrane lifetimes are considerably less than values in this table.
[b]Total = Stage A (average) + Stage B + Stage C (average)

area. Simulated stress tests under elevated-temperature testing and Arrhenius modelling is clearly the best route in this regard. Answers to the important question 'how long will they last?' may never be known unless such efforts are embraced and the result shared with the community at large.

3.6   Acknowledgements

3.7   References

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4

National and international standards governing geosynthetics

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4.1 Why standardization?

In any discussion concerning the development of any of the various types of standard for geosynthetics, the inevitable question is: 'why do we need standards?' There are several reasons that can be given.

1 In relation to testing, standards provide a consistent way to evaluate geosynthetics so that the end user can be assured that, irrespective of the laboratory that performs the testing, the results received will be within the acceptable statistical range for the material. In other words, the same result, within the statistical bounds of the standard, will be obtained irrespective of where tested, as long as the established protocol is followed.
2 The second point is where the controversy starts. Standardizing testing methods, material specifications, standards of practices, etc. allows for continued innovation. By standardizing those areas that can be standardized, it allows concentration on the development of new materials, and new ideas of application because of the first point above. In other words, with standardization, one does not have to concentrate on explaining variations in results of different testing methods for the same characteristic. Of course, this is predicated on the understanding that the standards are being followed as written.

4.2 Types of standard

The *Form and Style for ASTM Standard Manual*, (ASTM International, 2005a) defines four types of standard.

1 Standard test methods.
2 Standards of practice.
3 Standard guides.
4 Standard specifications.

The *ASTM Standard Manual* defines each as follows.

4.2.1 Standard test method

A standard test method provides detailed directions on performing specific tests, which produce a test result, e.g. ASTM D4491 *Standard Test Method for the Water Permeability of Geotextiles by the Permittivity Method*. The standard test method allows results of like tests performed by different laboratories to be compared. If performed as written, they will provide similar results within the statistical bounds of the method. The standard test method provides the basis for laboratory accreditation programmes. When accredited in a test method, not only has the laboratory demonstrated their ability to perform the test as written, but also that they have a quality assurance programme, perform routine maintenance of equipment and keep accurate records regarding testing and maintenance.

4.2.2 Standard of practice

A standard of practice is a compendium of information or series of options that does not recommend a specific course of action. A standard of practice is aimed at increasing the awareness of information and approaches in a given subject area, e.g. ASTM D4354 *Practice for Sampling of Geosynthetics for Testing.*

4.2.3 Standard guide

A guide is different from the previous two standards in that it provides a definitive set of instructions for performing one or more very specific operations that do not produce a test result, e.g. ASTM D4873 *Guide for Identification, Storage and Handling of Geosynthetic Rolls and Samples.*

4.2.4 Standard specification

A standard specification is an explicit set of requirements to be satisfied by a material, product, system or service. As related to geosynthetics, this may be divided into two subcategories.

1 Material property requirements.
2 Material performance.

Material property requirements

Material properties are set for two reasons: firstly, to establish purchasing criteria and, secondly, to provide the means for the purchasing organization to accept materials for use on their construction projects, e.g. ASTM D6817 *Standard Specification for Rigid Cellular Polystyrene Geofoam.*

Table 4.1 Standards development organizations

Country	Organization	Abbreviation
Austria	Österreichisches Normungs institut	ON
Australia	Standards Australia	SA
Belgium	Institut Belge de Normalisation	IBN
Canada	Standards Council of Canada	SCC
Denmark	Dansk Standard	DS
France	Association Française de Normalisation	AFNOR
Germany	Deutsches Institut für Normung	DIN
Italy	Ente Nazionale Italiano di Unificazione	UNI
Japan	Japanese Industrial Standards Committee	JISC
Korea	Korean Agency for Technology and Standards	KATS
Turkey	Turk Standards lari Enstitusu	TSE
UK	British Standards Institution	BSI
USA	American National Standards Institute	ANSI

Material performance

A material performance specification establishes a level of expected performance of a material to ensure the long term performance of the material. The American Association of State Highway and Transportation Officials (AASHTO) M-288 *Specification for Geotextiles* is aimed at this.

4.3   Standards development organizations

Within each country there may be one or more organizations that undertake the development of any of the types of standards described in Section 4.2. Some examples of such standards development organizations (SDOs) are shown in Table 4.1. A more detailed listing specific to geosynthetics will be described later in the chapter. The organizations shown in Table 4.1 are those SDOs that have been designated as the representative organization to the International Organization for Standardization (ISO). As indicated previously there may be more than one organization that undertakes the development of standards. Some are very specific in the areas that they work in, e.g. the International Electrotechnical Committee (IEC). Examples of some other SDOs within the USA are shown in Table 4.2. The

Table 4.2 Other standards development organizations within the USA

Name	Abbreviation
American Society of Testing and Materials International	ASTM
American Association of State Highway and Transportation Officials	AASHTO
National Institute for Standards and Technology	NIST

author of the chapter chose the USA as he is from the USA and therefore these are the SDOs that he is familiar with. Bodies within other countries of the world are indeed viable and just as crucial to the development of standards.

4.3.1   International standards development organizations

On the international level there are three main standards organizations that operate based on national representation to the areas of interest. These are as follows.

1 International Organization for Standardization (ISO).
2 European Committee for Standardization (Comité Européen de Normalisation, CEN).
3 ASTM International.

ISO is truly a worldwide organization, with representation to it coming from the designated national SDOs for each member country. CEN is also made up of representation from the designated national standards organization, but is limited to Europe. ASTM International is made up of individual members from around the world, has international offices in various parts of the world, and also has a wide distribution of its standards worldwide.

4.3.2   Standards development processes

Generally a standards development organization follows one of three processes in the development of its standards.

1 Consensus.
2 One country, one vote.
3 Weighted country vote.

The descriptions of each of these processes follow.

Consensus

In the consensus process, all negative votes and comments received on a balloted item must be considered and responded to before the document can proceed on to finalization. This does not mean that all negative votes and comments cause changes to be made to the proposed standard. First there has to be a technical reason given for the negative vote or comment. The committee that has jurisdiction over the proposed standard must consider the rationale for the negative vote. They may agree with it, which then does cause a change to be made, and reballoting taking place. If the committee does not agree with the negative vote, there must be a rationale given for not agreeing, and a vote taken to find the negative voter non-persuasive. If the rationale for finding the negative non-persuasive is upheld by the committee, the document proceeds on. If not, it is returned for reconsideration to

the working group which is developing it. In regard to comments, these are generally associated with affirmative votes, but the voter may have an idea that they wish to have considered without holding up the progress of the document. In this instance the comment is reviewed and the working group developing it may take one of several actions. It may choose to incorporate the idea of the comment into the standard, which then may require a reballot. It may decide that the comment is appropriate but, so as not to hold up progression of the document, they may agree to progress the document and then to undertake a revision immediately on final approval. The third option is they may not agree with the comment and may move the document on. There does not need to be a committee vote taken for any of the actions described related to comments received on a ballot document. In the consensus process, if it is determined that a negative vote was not addressed in the proper manner, the results of the ballot can be nullified, requiring a reballot.

Simple majority

In the simple majority process, the majority result of the ballot on a document rules. In this process, if there is majority affirmative vote, negative votes do not hold up a document from proceeding but still must be addressed. The risk in this process is that a document may proceed on even if a review of the negative votes determines that one or more of them has merit. In this instance the concern then has to be addressed by proposing a revision to the document, and the ballot process started all over again. A flawed document could be issued as a final approved standard before the flaw is corrected.

4.3.3   Voting structures

The various standards organizations have different ways of structuring their votes. There are three primary ways however, that should be explained.

Balanced membership

In a balanced membership structure, the number of members of voting producer organizations may not exceed the number of user and general-interest voting members. Also, each organization has only one official vote when it comes to determining whether there were a sufficient number of ballots returned to consider it a valid ballot. Every member receives a ballot and is encouraged to vote, but only the ballot of the official voting member of an organization is counted in determining the ballot return statistics. Whether an individual is a voting member or not, if they vote negative, their concern must be addressed as in the section above on the consensus process. An example of an organization which uses this structure is ASTM International. In the voting structure of ASTM International (2005b), the sum of all voting members' ballots returned must equal 60% of the total voting

Table 4.3 Voting requirements of ASTM International

Stage	Return requirement	Affirmative vote requirement
Subcommittee	60% of voting membership	Two thirds of combined affirmative and negative votes to be affirmative
Main committee	60% of voting membership	90% of combined affirmative and negative votes to be affirmative
Society review; concurrent with main committee ballot	Not applicable; comments and negatives must be handled as in other stages	

membership of the committee, or subcommittee in order to be considered a valid ballot. Table 4.3 shows a detailed description of voting requirements at the three stages of balloting for an ASTM International standard. Meeting of the voting requirements shown in Table 4.3 does not give immediate approval to a proposed or revised standard. The negatives votes and comments must be handled as previously described, and a review by the ASTM International Standing Committee on Standards be satisfied that this was done before final approval and publication.

One country, one vote

In the one country, one vote structure, membership on a committee is made up of delegations from each individual member country. There are 'participating' and 'observing' member classifications. Only the 'participating member' countries can vote on a document. The vote is issued through the official SDO representative to the overall committee parent organization. Irrespective of how large the representative delegation is, they have only one vote. An example of this structure can be found with the ISO. Table 4.4 details the voting requirements for the various types and stages of ISO documents (International Organization for Standardization, 2001).

Weighted voting

In the CEN voting system, when voting for a European Standard (EN), each country has been assigned a weighted vote. In order for the proposal to be adopted, 71% of the weighted votes cast (not including abstentions) must be in favour. If the proposal is not adopted, the weighted votes cast by European Economic Area countries shall be counted, with approval if 71% of these votes are in favour (European Committee for Standardization, 2002). Examples of these weightings are given in Table 4.5 (European Committee for Standardization, 2002). The

Table 4.4 Approval requirements of ISO[a]

Stage	International standard	Technical specification	Publicly available specification	Technical report
Proposal stage				
Adoption of new work item	SVAT score >15 Simple majority of P-members of the committee Five P-members participating Five experts named			Not applicable
Adoption of proposal for amendment or revision or transformation of deliverable	SVAT score >9 5 P-members participating Simple majority of P-members of the committee agree to the proposal			Not applicable
Preparatory stage				
Acceptance of WD for circulation as CD	Not defined; determined by the committee secretary in conjunction with the committee			
Committee stage				
Acceptance of CD for submission as DIS	Consensus, or Support from two thirds of the P-members voting	Support from two thirds of the P-members voting	Simple majority of P-members of the committee	
Enquiry stage				
Acceptance for submission as FDIS	Two thirds of P-members positive No more than one quarter of the votes negative		Not applicable	
Approval stage				
Agreement to publish	Two-thirds of P-members positive No more than one quarter of the votes negative		Not applicable	

[a]Abbreviations used in Table 4.4 are as follows: SVAT, standards value assessment tool; P-member, participating member; WD, working draft; CD, committee draft; DIS, draft international standard; FDIS, final draft international standard.

weightings are determined using a formula which takes into account a country's population and its gross national product. There are conditions under which a member country may appeal a vote. The complete listing is found in the CEN/

Table 4.5 Weighted votes of CEN

CEN member country	Weighted votes
UK	29
Poland	27
The Netherlands	13
Belgium	12
Sweden	10
Norway	7
Latvia	4
Malta	3

CENELEC Internal Regulations, Part 2, Clause 7 (European Committee for Standardization, 2002).

4.4   Geosynthetic standards

Based on the information in Section 4.3, one can understand that the development of geosynthetic standards is a lengthy process. However, in the end, irrespective of which SDO you work with, the standards that have been and are currently being developed are of the highest quality and most pertinent to the discipline.

4.4.1   Brief history of geosynthetic standardization

The author's earliest participation in the development of geosynthetic standards was in 1977 when the ASTM Committee D13 on Textiles formed a subcommittee to start work on developing test methods for what was then referred to as filter fabrics. Realizing that the subcommittee was not obtaining the needed input from the geotechnical community, a joint subcommittee was formed between Committee D13 and Committee D18 on Soil and Rock. In 1984, after making no progress towards approving any standards owing to the difficulty of handling negative votes through two different committees, with the approval of Committee D13, Committee D18 and ASTM Headquarters, Committee D35 on Geotextiles and Related Products, later changed to Committee D35 on Geosynthetics, was formed. The standards development within Committee D35 is accomplished through a number of subcommittees. A listing of these subcommittees and the scope of their work may be found on the ASTM International web site under Committee D35 (ASTM International, 2006).

ISO Technical Committee 221 on Geosynthetics

Like the ASTM D35 Committee, the ISO geosynthetics activity was originally a subcommittee under Technical Committee 38 on Textiles, Subcommittee 21 on Geotextiles. ISO Technical Committee 221 on Geosynthetics was approved by the

Technical Management Board of ISO in the year 2000. The work within Technical Committee 221 is accomplished through several working groups. These may be found on the ISO web site under ISO/TC 221 (International Organization for Standardization, 2006).

CEN Technical Committee 189 on Geosynthetics

The CEN Technical Committee 189 was formed in 1989, with its first work programme in 1990. Like ISO Technical Committee 221, the work of CEN Technical Committee 189 is also accomplished within several working groups. They may be found on the CEN web site under CEN/TC 189 (European Committee for Standardization, 2006)

4.4.2   Standards around the world

Table 4.6 is a listing of the reference numbers for the geosynthetic standards available at the time of preparation of this text through the three international standards organizations ASTM International, ISO and CEN. Specific information about the standards listed and any additional new standards is available through the respective SDO (ASTM International, 2006; European Committee for Standardization, 2006; International Organization for Standardization, 2006).

4.5   Future trends

Some may say that, since there are many existing standards within the geosynthetics community, what is left to do? The answer falls into two categories.

1   Work on existing standards.
2   Development of new standards.

4.5.1   Work on existing standards

There is a need to review and revise existing standards continually as experience is gained in their use. There is always new equipment being developed to perform existing methods better. As experience is gained, problems may be discovered that may affect the final results that are reported; maybe this is not a problem, but more efficient ways to perform testing may become evident. In the case of standard specifications, it may be found that material requirements need to be tightened up or improved to ensure the expected and desired performance. In all these cases, it will be necessary to review and revise the existing standard formally and to come to a consensus agreement on the appropriate revisions.

Table 4.6 Geosynthetic standards[a]

Property/subject	ASTM International Committee D35	Standards organization[5] ISO Technical Committee 221	CEN Technical Committee 189
Mechanical	D4354-99(2004) Standard Practice for Sampling of Geosynthetics for Test-ing	ISO 13426-1:2003 Geotextiles and Geotextile-related Products – Strength of Internal Structural Junctions – Part 1: Geocells	EN 13249:2000 Geotextiles and Geotextile-related Products – Characteristics Required for Use in the Construction of Roads and Other Trafficked Areas (excluding railways and asphalt inclusion)
	D4533-04 Standard Test Method for Trapezoid Tearing Strength of Geotextiles	ISO 13426-2:2005 Geotextiles and Geotextile-related Products – Strength of Internal Structural Junctions – Part 2: Geocomposites	EN 13249:2000/A1:2005 Geotextiles and Geotextile-related Products – Required Characteristics for Use in the Construction of Roads and Other Trafficked Areas
	D4595-86(2001) Standard Test Method for Tensile Properties of Geotextiles by the Wide-width Strip Method	ISO 12957-1:2005 Geosynthetics – Determination of Friction Characteristics – Part 1: Direct Shear Test	EN 13250:2000 Geotextiles and Geotextile-related Products – Characteristics Required for Use in the Construction of Railways
	D4632-91(2003) Standard Test Method for Grab Breaking Load and Elongation of Geotextiles	ISO 12957-2:2005 Geosynthetics – Determination of Friction Characteristics – Part 2: Inclined Plane Test	EN 13250:2000/A1:2005 Geotextiles and Geotextile-related Products – Required Characteristics for Use in the Construction of Railways
	D4759-02 Standard Practice for Determining the Specification Conformance of Geosynthetics	ISO 12236:1996 Geotextiles and Geotextile-related Products – Static Puncture Test (CBR test)	EN 13251:2000 Geotextiles and Geotextile-related Products – Characteristics Required for Use in Earthworks, Foundations and Retaining Structures
	D4833-00e1 Standard Test Method for Index Puncture Resistance of Geotextiles, Geomembranes, and Related Products	ISO 10321:1992 Geotextiles – Tensile Test for Joints/Seams by Wide-width Method	EN 13251:2000/A1:2005 Geotextiles and Geotextile-related Products – Required Characteristics for Use in
	D4884-96(2003) Standard Test Method for Strength of Sewn or Thermally Bonded Seams of Geotextiles	ISO 10320:1999 Geotextiles and Geotextile-related Products – Identification on Site	
	D5261-92(2003) Standard Test Method for Measuring Mass per Unit Area of Geotextiles	ISO 10319:1993 Geotextiles – Wide-width Tensile Test	

Table 4.6 Geosynthetic standards[a] (cont)

Property/subject	ASTM International Committee D35	Standards organization[5] ISO Technical Committee 221	CEN Technical Committee 189
Mechanical	D5321-02 Standard Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosyntheticand Geosynthetic Friction by the Direct Shear Method	ISO 9864:2005 Geosynthetics – Test Method for the Determination of Mass Per Unit Area of Geotextiles and Geotextile-related Products	Earthworks, Foundations and Retaining Structures EN 13256:2000 Geotextiles and Geotextile-related Products – Characteristics Required for Use in the Construction of Tunnels and Underground Structures
	D5818-95(2000) Standard Practice for Obtaining Samples of Geosynthetics from a Test Section for Assessment of Installation Damage	ISO 9863-1:2005 Geosynthetics – Determination of Thickness at Specified Pressures – Part 1: Single Layers	EN 13256:2000/A1:2005 Geotextiles and Geotextile-related Products – Required Characteristics for Use in the Construction of Tunnels and Underground Structures
	D6241-04 Standard Test Method for the Static Puncture Strength of Geotextiles and Geotextile-related Products Using a 50-mm Probe	ISO 9863-2:1996 Geotextiles and Geotextile-related Products – Determination of Thickness at Specified Pressures – Part 2: Procedure for Determination of Thickness of Single Layers of Multilayer Products	EN 13256:2000/AC:2003 Geotextiles and Geotextile-related Products – Characteristics for Use in the Construction of Tunnels and Underground Structures
	D6244-98(2004) Standard Test Method for Vertical Compression of Geocomposite Pavement Panel Drains	ISO 9862:2005 Geosynthetics – Sampling and Preparation of Test Specimens	EN 13257:2000 Geotextiles and Geotextile-related Products – Characteristics Required for Use in Solid Waste Disposals
	D6364-99(2004) Standard Test Method for Determining the Short-term Compression Behavior of Geosynthetics		EN 13257:2000/A1:2005 Geotextiles and Geotextile-related Products – Characteristics Required for Use in Solid Waste Disposals
	D6637-01 Standard Test Method for Determining Tensile Properties of Geogrids by the Single or Multi-rib Tensile Method		EN 13257:2000/AC:2003 Geotextiles and Geotextile-related Products –
	D6638-01 Standard Test Method for		

Determining Connection Strength Between Geosynthetic Reinforcement and Segmental Concrete Units (Modular Concrete Blocks)
D6706-01 *Standard Test Method for Measuring Geosynthetic Pullout Resistance in Soil*
D6916-03 *Standard Test Method for Determining the Shear Strength Between Segmental Concrete Units (Modular Concrete Blocks)*
D7005-03 *Standard Test Method for Determining the Bond Strength (Ply Adhesion) of Geocomposites*
D7179-05 *Standard Test Method for Determining Geonet Breaking Force*

Characteristics Required for Use in Solid Waste Disposals
EN 13265:2000 *Geotextiles and Geotextile-related Products – Characteristics Required for Use in Liquid Waste Containment Projects*
EN 13265:2000/A1:2005 *Geotextiles and Geotextile-related Products – Characteristics Required for Use in Liquid Waste Containment Projects*
EN 13265:2000/AC:2003 *Geotextiles and Geotextile-related Products – Characteristics Required for Use in Liquid Waste Containment Projects*
EN 13738:2004 *Geotextiles and Geotextile-related Products – Determination of Pullout Resistance in Soil*
EN 14574:2004 *Geosynthetics – Determination of the Pyramid Puncture Resistance of Supported Geosynthetics*
EN 918:1995 *Geotextiles and Geo-textile-related Products – Dynamic Perforation Test (Cone Drop Test)*
EN ISO 10319:1996 *Geotextiles – Wide-width Tensile Test* (ISO 10319:1993)
EN ISO 10321:1996 *Geotextiles – Tensile Test for Joints/Seams by Wide-width Method* (ISO 10321:1992)

Table 4.6 Geosynthetic standards[a] (*cont.*)

Property/subject	ASTM International Committee D35	Standards organization[5] ISO Technical Committee 221	CEN Technical Committee 189
Mechanical			EN ISO 12236:1996 *Geotextiles and Geotextile-related Products – Static Puncture Test (CBR-Test)* (ISO 12236:1996) EN ISO 12957-1:2005 *Geosynthetics – Determination of Friction Characteristics – Part 1: Direct Shear Test* (ISO 12957-1:2005) EN ISO 12957-2:2005 *Geosynthetics – Determination of Friction Characteristics – Part 2: Inclined Plane Test* (ISO 12957-2:2005) EN ISO 13426-1:2003 *Geotextiles and Geotextile-related Products – Strength of Internal Structural Junctions – Part 1: Geocells* (ISO 13426-1:2003) EN ISO 13426-2:2005 *Geotextiles and Geotextile-related Products – Strength of Internal Structural Junctions – Part 2: Geocomposites* (ISO 13426-2:2005) EN ISO 13427:1998 *Geotextiles and Geotextile-related Products – Abrasion Damage Simulation (Sliding Block Test)* (ISO 13427:1998)

			EN ISO 13428:2005 *Geosynthetics – Determination of the Protection Efficiency of a Geosynthetic Against Impact Damage (*ISO 13428:2005) EN ISO 9862:2005 *Geosynthetics – Sampling and Preparation of Test Specimens* (ISO 9862:2005) EN ISO 9863-1:2005 *Geosynthetics – Determination of Thickness at Specified Pressures – Part 1: Single Layers* (ISO 9863-1:2005) EN ISO 9863-2:1996 *Geotextiles and Geotextile-related Products – Determination of Thickness at specified Pressures – Part 2: Procedure for Determination of Thickness of Single Layers of Multilayer Products* (ISO 9863-2:1996) EN ISO 9864:2005 *Geosynthetics – Test Method for the Determination of Mass Per Unit Area of Geotextiles and Geotextile-related Products* (ISO 9864:2005)
Hydraulic	D4491-99a(2004) *Standard Test Methods for Water Permeability of Geotextiles by Permittivity* D4716-04 *Test Method for Determining the (In-plane) Flow Rate per Unit Width and Hydraulic Transmissivity of a Geosynthetic Using a Constant Head*	ISO 12958:1999 *Geotextiles and Geotextile-related Products – Determination of Water Flow Capacity in their Plane* ISO 12956:1999 *Geotextiles and Geotextile-related Products – Determination of the Characteristic Opening Size*	EN 12447:2001 *Geotextiles and Geotextile-related Products – Screening Test Method for Determining the Resistance to Hydrolysis in Water* EN 13252:2000 *Geotextiles and Geotextile-related Products –*

Table 4.6 Geosynthetic standards[a] (*cont.*)

Property/subject	ASTM International Committee D35	Standards organization[5] ISO Technical Committee 221	CEN Technical Committee 189
Hydraulic	D4751-04 *Standard Test Method for Determining Apparent Opening Size of a Geotextile* D5101-01 *Standard Test Method for Measuring the Soil–Geotextile System Clogging Potential by the Gradient Ratio* D5141-96(2004) *Standard Test Method for Determining Filtering Efficiency and Flow Rate of a Geotextile for Silt Fence Application Using Site-specific Soil* D5199-01 *Standard Test Method for Measuring the Nominal Thickness of Geosynthetics* D5493-93(2003) *Standard Test Method for Permittivity of Geotextiles Under Load* D5567-94(2001) *Standard Test Method for Hydraulic Conductivity Ratio (HCR) Testing of Soil/ Geotextile Systems* D6088-97(2002) *Standard Practice for Installation of Geocomposite Pavement Drains* D6140-00 *Standard Test Method to Determine Asphalt Retention of*	ISO 11058:1999 *Geotextiles and Geotextile-related Products – Determination of Water Permeability Characteristics Normal to the Plane, Without Load*	*Characteristics Required for Use in Drainage Systems* EN 13252:2000/A1:2005 *Geotextiles and Geotextile-related Products – Required Characteristics for Use in Drainage Systems* EN 13254:2000 *Geotextiles and Geotextile-related Products – Characteristics Required for Use in the Construction of Reservoirs and Dams* EN 13254:2000/A1:2005 *Geotextiles and Geotextile-related Products – Required characteristics for Use in the Construction of Reservoirs and Dams* EN 13254:2000/AC:2003 *Geotextiles and Geotextile-related Products – Characteristics Required for Use in the Construction of Reservoirs and Dams* EN 13255:2000 *Geotextiles and Geotextile-related Products – Characteristics Required for Use in the Construction of Canals* EN 13255:2000/A1:2005 *Geotextiles and Geotextile-related Products –*

*Paving Fabrics Used in Asphalt
Paving for Full-width Applications*
D6523-00 *Standard Guide for
Evaluation and Selection of
Alternative Daily Covers (ADCs) for
Sanitary Landfills*
D6574-00 *Test Method for
Determining the (In-Plane)
Hydraulic Transmissivity of a
Geosynthetic by Radial Flow*
D6707-01 *Standard Specification
for Circular-knit Geotextile for Use
in Subsurface Drainage
Applications*
D6767-02 *Standard Test Method for
Pore Size Characteristics of
Geotextiles by Capillary Flow Test*
D6817-04 *Standard Specification
for Rigid Cellular Polystyrene
Geofoam*
D6826-05 *Standard Specification
for Sprayed Slurries, Foams and
Indigenous Materials Used As
Alternative Daily Cover for
Municipal Solid Waste Landfills*
D6917-03 *Standard Guide for
Selection of Test Methods for
Prefabricated Vertical Drains (PVD)*
D6918-03 *Standard Test Method for
Testing Vertical Strip Drains in the
Crimped Condition*
D7001-05 *Standard Specification*

*Required Characteristics for Use in
the Construction of Canals*
EN 13255:2000/AC:2003 *Geotextiles
and Geotextile-related Products –
Characteristics Required for Use in
the Construction of Canals*
EN 13562:2000 *Geotextiles and
Geotextile-related Products –
Determination of Resistance to
Penetration by Water (Hydrostatic
Pressure Test)*
EN ISO 11058:1999 *Geotextiles and
Geotextile-related Products –
Determination of Water
Permeability Characteristics Normal
to the Plane, Without Load* (ISO
11058:1999)
EN ISO 12956:1999 *Geotextiles and
Geotextile-related Products –
Determination of the Characteristic
Opening Size* (ISO 12956:1999)
EN ISO 12958:1999 *Geotextiles and
Geotextile-related Products –
Determination of Water Flow
Capacity in Their Plane* (ISO
12958:1999)

Property/subject	ASTM International Committee D35	Standards organization[5]	
		ISO Technical Committee 221	CEN Technical Committee 189
Hydraulic	for *Geocomposites for Pavement Edge Drains and Other High-flow Applications* D7008-03 *Standard Specification for Geosynthetic Alternate Daily Covers* D7180-05 *Standard Guide for Use of Expanded Polystyrene (EPS) Geofoam in Geotechnical Projects*		
Durability	D1987-95(2002) *Standard Test Method for Biological Clogging of Geotextile or Soil/Geotextile Filters* D4355-05 *Standard Test Method for Deterioration of Geotextiles by Exposure to Light, Moisture and Heat in a Xenon Arc Type Apparatus* D4594-96(2003) *Standard Test Method for Effects of Temperature on Stability of Geotextiles* D4873-02 *Standard Guide for Identification, Storage, and Handling of Geosynthetic Rolls and Samples* D4886-88(2002) *Standard Test Method for Abrasion Resistance of*	ISO 13438:2004 *Geotextiles and Geotextile-related Products – Screening Test Method for Determining the Resistance to Oxidation* ISO 13437:1998 *Geotextiles and Geotextile-related Products – Method for Installing and Extracting Samples in Soil, and Testing Specimens in Laboratory* ISO/TR 13434:1998 Geotextiles and Geotextile-related Products – Guidelines on Durability ISO 13431:1999 *Geotextiles and Geotextile-related Products – Determination of Tensile Creep and Creep Rupture Behaviour*	CEN/TR 15019 *Geotextiles and Geotextile-related Products – On-site Quality Control:2005* CR ISO 13434:1998 *Guidelines on Durability of Geotextiles and Geotextile-related Products* EN 12224:2000 *Geotextiles and Geotextile-related Products – Determination of the Resistance to Weathering* EN 12225:2000 *Geotextiles and Geotextile-related Products – Method for Determining the Microbiological Resistance by a Soil Burial Test* EN 12226:2000 *Geotextiles and Geotextile-related Products –*

Geotextiles (Sand Paper/Sliding Block Method)

D5262-04 Standard Test Method for Evaluating the Unconfined Tension Creep Behavior of Geosynthetics

D5322-98(2003) Standard Practice for Immersion Procedures for Evaluating the Chemical Resistance of Geosynthetics to Liquids

D5397-99e1 Standard Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test

D5496-98(2003) Standard Practice for In Field Immersion Testing of Geosynthetics

D5596-03 Standard Test Method for Microscopic Evaluation of the Dispersion of Carbon Black in Polyolefin Geosynthetics

D5721-95(2002) Standard Practice for Air–Oven Aging of Polyolefin Geomembranes

D5747-95a(2002) Standard Practice for Tests to Evaluate the Chemical Resistance of Geomembranes to Liquids

D5819-05 Standard Guide for Selecting Test Methods for Experimental Evaluation of Geosynthetic Durability

ISO 13428:2005 *Geosynthetics – Determination of the Protection Efficiency of a Geosynthetic Against Impact Damage*

ISO 13427:1998 *Geotextiles and Geotextile-related Products – Abrasion Damage Simulation (Sliding Block Test)*

ISO/TR 12960:1998 *Geotextiles and Geotextile-related Products – Screening Test Method for Determining the Resistance to Liquids*

ISO/TR 10722-1:1998 *Geotextiles and Geotextile-related Products – Procedure for Simulating Damage During Installation – Part 1: Installation in Granular Materials*

General Tests for Evaluation Following Durability Testing

EN 14030:2001 *Geotextiles and Geotextile-related Products – Screening Test Method for Determining the Resistance to Acid and Alkaline Liquids* (ISO/TR 12960:1998, modified)

EN 14030:2001/A1:2003 *Geotextiles and Geotextile-related Products – Screening Test Method for Determining the Resistance to Acid and Alkaline Liquid*s (ISO/TR 12960:1998, modified)

EN 14414:2004 *Geosynthetics – Screening Test Method for Determining Chemical Resistance for Landfill Applications*

EN 1897:2001 *Geotextiles and Geotextile-related Products – Determination of the Compressive Creep Properties*

EN ISO 10320:1999 *Geotextiles and Geotextile-related Products – Identification on Site* (ISO 10320:1999)

EN ISO 13431:1999 *Geotextiles and Geotextile-related Products – Determination of Tensile Creep and Creep Rupture Behaviour* (ISO 13431:1999)

EN ISO 13437:1998 *Geotextiles and*

Table 4.6 Geosynthetic standards[a] (*cont.*)

Property/subject	ASTM International Committee D35	Standards organization[5] ISO Technical Committee 221	CEN Technical Committee 189
Durability	D5885-04 *Standard Test Method for Oxidative Induction Time of Polyolefin Geosynthetics by High-Pressure Differential Scanning Calorimetry* D5970-96(2002) *Standard Practice for Deterioration of Geotextiles from Outdoor Exposure* D6213-97(2003) *Standard Practice for Tests to Evaluate the Chemical Resistance of Geogrids to Liquids* D6388-99 *Standard Practice for Tests to Evaluate the Chemical Resistance of Geonets to Liquids* D6389-99 *Standard Practice for Tests to Evaluate the Chemical Resistance of Geotextiles to Liquids* D6992-03 *Standard Test Method for Accelerated Tensile Creep and Creep-rupture of Geosynthetic Materials Based on Time–Temperature Superposition Using the Stepped Isothermal Method*		*Geotextile-related Products – Method for Installing and Extracting Samples in Soil, and Testing Specimens in Laboratory* (ISO 13437:1998 EN ISO 13438:2004 *Geotextiles and Geotextile-related Products – Screening Test Method for Determining the Resistance to Oxidation* (ISO 13438:2004) ENV ISO 10722-1:1998 *Geotextiles and Geotextile-related Products – Procedure for Simulating Damage During Installation – Part 1: Installation in Granular Materials* (ISO 10722-1:1998)

Geosynthetic liners; also known as clay geosynthetic barriers

D5887-04 *Standard Test Method for Measurement of Index Flux Through Saturated Geosynthetic Clay Liner Specimens Using a Flexible Wall Permeameter*
D5888-95(2002)e1 *Standard Guide for Storage and Handling of Geosynthetic Clay Liners*
D5889-97(2003) *Standard Practice for Quality Control of Geosynthetic Clay Liners*
D5890-02 *Standard Test Method for Swell Index of Clay Mineral Component of Geosynthetic Clay Liners*
D5891-02 *Standard Test Method for Fluid Loss of Clay Component of Geosynthetic Clay Liners*
D5993-99(2004) *Standard Test Method for Measuring Mass Per Unit of Geosynthetic Clay Liners*
D6072-96(2002) *Standard Guide for Obtaining Samples of Geosynthetic Clay Liners*
D6102-04 *Standard Guide for Installation of Geosynthetic Clay Liners*
D6141-97(2004) *Standard Guide for Screening Clay Portion of Geosynthetic Clay Liner (GCL) for Chemical Compatibility to Liquids*
D6243-98 *Standard Test Method for*

EN 13361:2004 *Geosynthetic Barriers – Characteristics Required for Use in the Construction of Reservoirs and Dams*
EN *13362:2005 Geosynthetic Barriers – Characteristics Required for Use in the Construction of Canals*
EN 13491:2004 *Geosynthetic Barriers – Characteristics Required for Use as a Fluid Barrier in the Construction of Tunnels and Underground Structures*
EN 13492:2004 *Geosynthetic Barriers – Characteristics Required for Use in the Construction of Liquid Waste Disposal Sites, Transfer Stations or Secondary Containment*
EN 13493:2005 *Geosynthetic Barriers – Characteristics Required for Use in the Construction of Solid Waste Storage and Disposal Sites*
EN 13719:2002 *Geotextiles and Geotextile-related Products – Determination of the Long Term Protection Efficiency of Geotextiles in Contact with Geosynthetic Barriers*
EN 13719:2002/AC:2005 *Geotextiles and Geotextile-related Products – Determination of the Long Term Protection Efficiency of Geotextiles*

Table 4.6 Geosynthetic standards[a] (*cont.*)

| Property/subject | Standards organization[5] | | |
	ASTM International Committee D35	ISO Technical Committee 221	CEN Technical Committee 189
Geosynthetic liners; also known as clay geosynthetic barriers	*Determining the Internal and Interface Shear Resistance of Geosynthetic Clay Liner by the Direct Shear Method* D6495-02 *Standard Guide for Acceptance Testing Requirements for Geosynthetic Clay Liners* D6496-04a *Standard Test Method for Determining Average Bonding Peel Strength Between the Top and Bottom Layers of Needle-Punched Geosynthetic Clay Liners* D6766-02 *Standard Test Method for Evaluation of Hydraulic Properties of Geosynthetic Clay Liners Permeated with Potentially Incompatible Liquids* D6768-04 *Standard Test Method for Tensile Strength of Geosynthetic Clay Liners*		*in Contact with Geosynthetic Barriers* EN 14196:2003 *Geosynthetics – Test Methods for Measuring Mass Per Unit Area of Clay Geosynthetic Barriers* EN 14415:2004 *Geosynthetic Barriers – Test Method for Determining the Resistance to Leaching* EN 14575:2005 *Geosynthetic Barriers – Screening Test Method for Determining the Resistance to Oxidation* EN 14576:2005 *Geosynthetics – Test Method for Determining the Resistance of Polymeric Geosynthetic Barriers to Environmental Stress Cracking*

Geomembranes   D4437-99 *Standard Practice for Determining the Integrity of Field Seams Used in Joining Flexible Polymeric Sheet Geomembranes*
D4545-86(1999) *Standard Practice for Determining the Integrity of Factory Seams Used in Joining Manufactured Flexible Sheet geomembranes*
D4885-01 *Standard Test Method for Determining Performance Strength of Geomembranes by the Wide Strip Tensile Method*
D5323-92(1999) *Standard Practice for Determination of 2% Secant Modulus for Polyethylene Geomembranes*
D5494-93(1999)e1 *Standard Test Method for the Determination of Pyramid Puncture Resistance of Unprotected and Protected Geomembranes*
D5514-94(2001) *Standard Test Method for Large Scale Hydrostatic Puncture Testing of Geosynthetics*
D5617-04 *Standard Test Method for Multi-axial Tension Test for Geosynthetics*
D5641-94(2001)e1 *Standard Practice for Geomembrane Seam Evaluation by Vacuum Chamber*
D5820-95(2001)e1 *Standard*

Table 4.6 Geosynthetic standards[a] (*cont.*)

Property/subject	ASTM International Committee D35	Standards organization[5]	
		ISO Technical Committee 221	CEN Technical Committee 189
Geomembranes	*Practice for Pressurized Air Channel Evaluation of Dual Seamed Geomembranes*		
	D5884-04a *Standard Test Method for Determining Tearing Strength of Internally Reinforced Geomembranes*		
	D5886-95(2001) *Standard Guide for Selection of Test Methods to Determine Rate of Fluid Permeation Through Geomembranes for Specific Applications*		
	D5994-98(2003) *Standard Test Method for Measuring Core Thickness of Textured Geomembrane*		
	D6214-98(2003) *Standard Test Method for Determining the Integrity of Field Seams Used in Joining Geomembranes by Chemical Fusion Methods*		
	D6365-99 *Standard Practice for the Nondestructive Testing of Geomembrane Seams using the Spark Test*		
	D6392-99 *Standard Test Method for Determining the Integrity of*		

Nonreinforced Geomembrane Seams Produced Using Thermo-fusion Methods
D6434-04 *Standard Guide for the Selection of Test Methods for Flexible Polypropylene (fPP) Geomembranes*
D6455-99 *Standard Guide for the Selection of Test Methods for Prefabricated Bituminous Geomembranes (PBGM)*
D6497-02 *Standard Guide for Mechanical Attachment of Geomembrane to Penetrations or Structures*
D6636-01 *Standard Test Method for Determination of Ply Adhesion Strength of Reinforced Geomembranes*
D6693-04 *Standard Test Method for Determining Tensile Properties of Nonreinforced Polyethylene and Nonreinforced Flexible Polypropylene Geomembranes*
D6747-04 *Standard Guide for Selection of Techniques for Electrical Detection of Potential Leak Paths in Geomembrane*
D7002-03 *Standard Practice for Leak Location on Exposed Geomembranes Using the Water Puddle System*

Table 4.6 Geosynthetic standards[a] (*cont.*)

Property/subject	ASTM International Committee D35	Standards organization[5]	
		ISO Technical Committee 221	CEN Technical Committee 189
Geomembranes	D7003-03 *Standard Test Method for Strip Tensile Properties of Reinforced Geomembranes*		
	D7004-03 *Standard Test Method for Grab Tensile Properties of Reinforced Geomembranes*		
	D7006-03 *Standard Practice for Ultrasonic Testing of Geomembranes*		
	D7007-03 *Standard Practices for Electrical Methods for Locating Leaks in Geomembranes Covered with Water or Earth Materials*		
	D7056-04 *Standard Test Method for Determining the Tensile Shear Strength of Pre-fabricated Bituminous Geomembrane Seams*		
	D7106-05 *Standard Guide for Selection of Test Methods for Ethylene Propylene Diene Terpolymer (EPDM) Geomembranes*		
	D7177-05 *Standard Specification for Air Channel Evaluation of Polyvinyl Chloride (PVC) Dual Track Seamed Geomembranes*		

Erosion control	D6454-99 *Standard Test Method for Determining the Short-term Compression Behavior of Turf Reinforcement Mats (TRMs)* D6524-00 *Standard Test Method for Measuring the Resiliency of Turf Reinforcement Mats (TRMs)* D6525-00 *Standard Test Method for Measuring Nominal Thickness of Permanent Rolled Erosion Control Products* D6566-00 *Standard Test Method for Measuring Mass per Unit Area of Turf Reinforcement Mats* D6567-00 *Standard Test Method for Measuring the Light Penetration of a Turf Reinforcement Mat (TRM)* D6575-00 *Standard Test Method for Determining Stiffness of Geosynthetics Used as Turf Reinforcement Mats (TRM's)* D6818-02 *Standard Test Method for Ultimate Tensile Properties of Turf Reinforcement Mats*		EN 13253:2000 *Geotextiles and Geotextile-related Products – Characteristics Required for Use in Erosion Control Works (Coastal Protection, Bank Revetments)* EN 13253:2000/A1:2005 *Geotextiles and Geotextile-related Products – Required Characteristics for Use in External Erosion Control Systems*
Terminology	D4439-04 Standard Terminology for Geosynthetics	ISO 10318:2005 Geosynthetics – Terms and Definitions	EN ISO 10318:2005 Geosynthetics – Terms and Definitions (ISO 10318:2005)

[a]As you move horizontally across the columns of Table 4.6, standards may not necessarily be the corresponding standard between each SDO. You may have to move vertically to find a corresponding standard.

4.5.2   Development of new standards

As new materials and new products are developed, it will become necessary to go through the same sort of test method development as has been done for the existing geosynthetics. It may become evident that even for the existing materials and products, because of a new use, or a problem occurring with their use, that a new better method of evaluation is needed.

4.5.3   Avoiding duplication of efforts

Looking down through Table 4.6 it becomes very evident that, just between the three SDOs listed there, it appears that each SDO has standards that will provide the same basic information. There may be minor or insignificant differences between the methods that will not have an effect on the final information reported for each, or there may be some major differences which will produce some values or information to be reported by each. The geosynthetics industry has truly become a global industry with manufacturers of products in just about all regions of the world. Most of these companies are not confined to doing business in their regions but have and are providing materials worldwide. If they are required to test or provide materials meeting the requirements of basically the same methods but to follow the standards particular to that region, it is very evident that the economic effect on the manufacturer can be great.

4.5.4   Efforts to avoid duplication

There have been efforts on the parts of the three committees shown in Table 4.6 to avoid duplication but, for reasons beyond the scope of this chapter, it has been very difficult to implement plans that had been devised to accomplish this. That said, the committees still are working among themselves to avoid duplicative efforts. Economics is not the only reason that concerted efforts need to be made to avoid duplicative work. It is time wasted if there is already a readily acceptable standard within another SDO for a group of people to spend time 'reinventing the wheel,' when they could be moving on to other areas that need work and where there may not already be a standard in existence.

4.6   Conclusions

It was stated at the beginning of this chapter that there is a definite need for standardization in the field of geosynthetics. It provides the end user with the ability to be comfortable that, at least in the testing area, the results of tests performed by one laboratory can be reproduced within statistical limits by another laboratory, provided that the same testing protocol is followed. For manufacturers, they then do not have to incur the expense of having the same products tested by

however many different procedures for the same test there might be. From standardized specifications, the manufacturers would then not have to produce many different products to meet the many different requirements that appear in specifications for the same end use. Standardization also provides the opportunity to focus on innovation and development of new products to meet the needs of the engineering community.

4.7   References

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