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Geosynthetics — Guidelines for the assessment of durability

Géosynthétiques — Lignes directrices concernant la durabilité

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

ISO/TS 13434 was prepared by Technical Committee ISO/TC 221, *Geosynthetics*.

This first edition cancels and replaces ISO/TS 13434:2008, which has been technically revised. The main changes compared to the previous edition are as follows:

- standards and wording actualized;
- added product types in 5.1;
- updated subclauses 5.4, 8.4, 8.5 and Table 3.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Geosynthetics — Guidelines for the assessment of durability

1 Scope

This document provides guidelines for the assessment of the durability of geosynthetics, the object of which is to provide the design engineer with the necessary information, generally defined as changes in material properties or as partial safety factors, to ensure that the expected design life of a geosynthetic can be achieved with confidence.

This document is not applicable to products designed to survive for only a limited time, such as erosion-control fabric based on natural fibres.

This document is applicable to the durability of the geosynthetics and not to the durability of the geotechnical structure as a whole.

NOTE The calculation of reduction factors for soil reinforcement applications is described in ISO/TR 20432.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10318-1, *Geosynthetics — Part 1: Terms and definitions*

ISO 13431, *Geotextiles and geotextile-related products — Determination of tensile creep and creep rupture behaviour*

ISO 13438:2018, *Geosynthetics — Screening test method for determining the resistance of geotextiles and geotextile-related products to oxidation*

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 10318-1 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at https://www.iso.org/obp
- IEC Electropedia: available at http://www.electropedia.org/

3.2 Symbols

A	rate of degradation
A_0	constant in Arrhenius equation
d_{50}	50 % soil gradation
E	activation energy

M_n	number-averaged molecular weight
M_w	weight-averaged molecular weight
R	universal gas constant (8,314 J/mol·K)
t_g	glass transition temperature
T	absolute temperature

3.3 Abbreviated items

CMD	cross-machine direction
CPE	chlorinated polyethylene
CSPE	chlorosulfonated polyethylene
DSC	differential scanning calorimetry
EIA	ethylene interpolymer alloy
ENB	ethylidene norbornene
EPDM	ethylene propylene diene monomer
EPS	expanded polystyrene
ESC	environmental stress cracking
fPP	flexible polypropylene
GBR-B	bituminous geosynthetic barrier
GBR-C	geosynthetic clay barrier
GBR-P	polymeric geosynthetic barrier
HALS	hindered amine light stabilizers
PE-HD	high-density polyethylene
HP-OIT	high-pressure oxidation induction time
KEE	ketone ethylene ester
PE-LLD	linear low-density polyethylene
MB	modified bitumen
MD	machine direction
OIT	oxidation induction time
PA	polyamide
PCM	post-consumer material
PE	polyethylene
PEN	polyethylene naphthalate

PET	polyethylene terephthalate
PIM	post-industrial material
PP	polypropylene
PS	polystyrene
PVAL	polyvinyl alcohol
PVC-P	flexible polyvinyl chloride
RPP	reinforced polypropylene
RWM	reworked material
SBS	styrene-butadiene-styrene
S-OIT	oxidation induction time measured by standard method
XPS	extruded polystyrene
UV	ultraviolet

4 Generalized procedure

4.1 General

When a geosynthetic is used in a civil engineering structure, it is intended to perform a particular function for a minimum expected time, called the design life. A geosynthetic is a generic term describing a product, where at least one of the components is made from a synthetic or natural polymer, in the form of a sheet, a strip or a three-dimensional structure, used in contact with soil and/or other materials in geotechnical and civil engineering applications. Geosynthetic products comprise geotextiles, geosynthetic barriers (polymeric, bituminous and geosynthetic clay liners), geogrids, geonets, geocells, geostrips, geomats, geoblankets, geocomposites and geospacers. The eight functions defined in ISO 10318-1 are barrier function, drainage, filtration, protection, reinforcement, separation, stabilisation, stress relief for asphalt overlay and surface erosion control. Each function uses one or more properties of the geosynthetic, such as tensile strength or water permeability for a geotextile and impermeability to liquids for a geosynthetic barrier. These are referred to as functional properties.

Assessment of the durability of structures using geosynthetics requires a study of the effects of time on the functional properties. The physical structure of the geosynthetic, the nature of the polymer used, the manufacturing process, the physical and chemical environment, the conditions of storage and installation, and the load supported by the geosynthetic are all parameters which govern the durability. The main task is to understand and assess the evolution of the functional properties over the entire design life. This problem is quite complex due to the combination and interaction of numerous parameters present in the soil environment, and to the lack of well-documented experience.

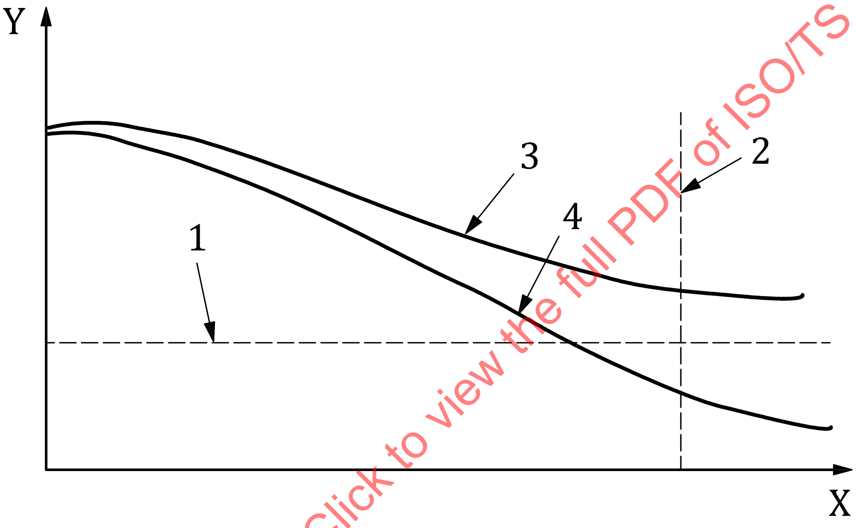
The majority of geosynthetics, when correctly processed and stabilized, are comparatively resistant to chemical and microbiological attack encountered in normal soil environments and for normal design lives. For such applications, only a minimum number of screening or index tests may be necessary. For applications in more severe environments, such as soil treated with lime or cement, landfills or industrial-waste containments, or for applications with particularly long design lives, special tests including "performance" tests with site-specific parameters may be required.

4.2 Available and required properties

4.2.1 Condition of acceptability

A geosynthetic will have one or more functional properties critical to its intended function, for example tensile strength or permeability. It is then necessary to differentiate between the available and required values of this functional property. The available property is that provided by the geosynthetic. The required property is the minimum level necessary for the geosynthetic to perform its intended function.

The available property is expected to change with time due to degradation of the material, as shown in Figure 1. The necessary condition is that, at the design lifetime (Item 2 in Figure 1), the available property exceeds the required property, which is shown for simplicity as remaining constant in time (Item 1). This condition is satisfied under the first set of conditions (Item 3) and is not satisfied under the second set of conditions (Item 4). These are therefore deemed to be acceptable and not acceptable, respectively.



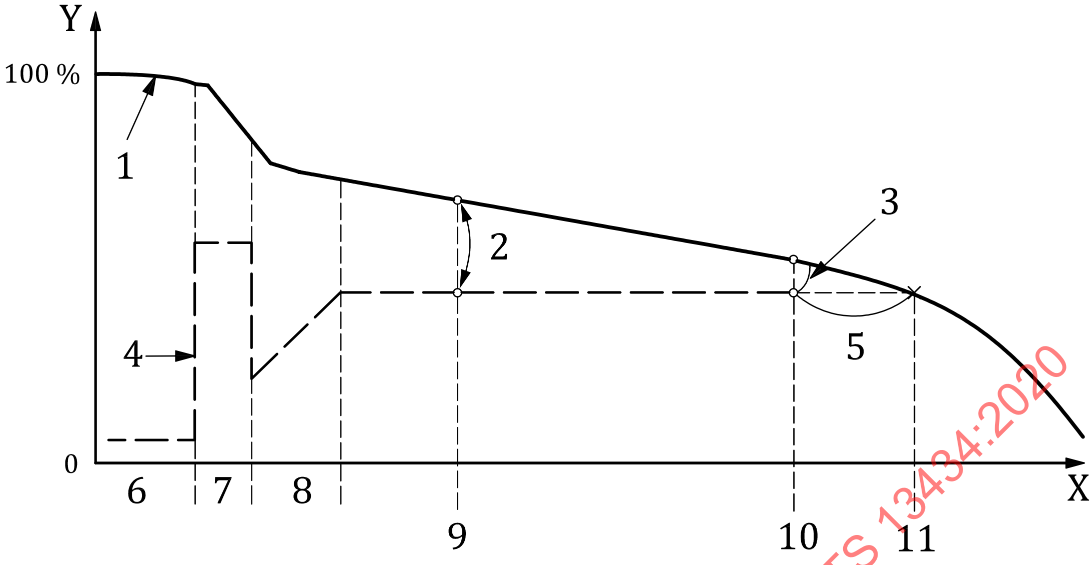
Key

X	time
Y	property of a geosynthetic, expressed as a percentage of its original value
1	minimum acceptable level of required property
2	design lifetime
3	available property under first set of conditions (acceptable)
4	available property under second set of conditions (not acceptable)

Figure 1 — Available and required properties as a function of time under two different sets of conditions, the first acceptable and the second not acceptable

4.2.2 Development of the required and available properties with time

In practice, both the available property and the required property can vary with the successive events that occur between manufacture of the product and the design life. Figure 2 shows a schematic example.



Key

X time

Y property of a geosynthetic, expressed as a percentage of its original value

1 available property

2 margin between required and available property at intermediate time

3 margin of safety at design life

4 required property

5 margin of safety between design life and time to failure

6 duration prior to installation (storage and transportation)

7 duration of installation and covering

8 duration of further construction

9 intermediate time during normal use

10 design life

11 time to failure

Figure 2 — Available and required properties of a geosynthetic during storage and transportation, construction, backfilling and use

A new geosynthetic exhibits an initial or short-term available property as defined by a set measurement standard. Depending on the level of quality control and quality assurance, a reduction factor may be applied to cover variations in the initial property.

The available property is shown as line 1 in Figure 2. During storage and transportation (period 6 in Figure 2), this property may change due to weathering, while during installation (period 7) and further construction (period 8), it may suffer from mechanical damage. The extent of the mechanical damage incurred during installation depends on the geosynthetic, the nature of the materials in contact with the geosynthetic, the equipment used and the care provided by the handling team (see 6.4.4). For polymeric geosynthetic barriers, the manufacturing process and the welding parameters during installation may not lead to immediate degradation, but can induce residual stresses in the material which lead to a stress-crack phenomenon and more rapid subsequent degradation.

After backfilling (period 8), the operating life of the material starts. During the operating life, the geosynthetic is subjected to chemical, biological or physical actions due to the soil, its constituents, and its air, water and organic content, resulting in a gradual reduction in the available property until the design life (Item 10 in Figure 2) is reached. The available property will diminish further if the geosynthetic remains in place beyond its design life.

The required property is shown as line 4 in Figure 2. During storage and transportation (period 6 in Figure 2), a minimum required property, generally strength, is needed to resist handling loads. Installation and compaction (period 7) may require a strength higher than that required for the remainder of the design life. During further construction (period 8), the load will increase from a lower level, increasing the required strength. When finally in use, the required property will remain constant.

It should be noted that the available property can diminish due to the level of constraints or the applied load: the greater the applied stress, the shorter the time to failure. This is a particularly important phenomenon that is described in 6.4, particularly in 6.4.1. Thus, there can be an interaction between the required property and the available property. There is no absolute available property curve as shown schematically in the graph by the presence of the two curves.

It should also be noted that there may be more than one functional property. For example, a filter or separator will have a minimum required strength to survive installation and construction, while in operation the required property will be the permeability or opening size. The above analysis should be performed for both properties.

The testing techniques and the assessment methods for estimating the property curves is presented and discussed in later subclauses. Index test methods are intended to ensure a minimum level of durability and do not constitute a comprehensive assessment procedure. Where this is needed, it will be necessary to carry out further performance tests more closely related to service conditions. These tests may also include investigations on samples extracted from sites where the same product has been used for several years in a similar environment. Procedures have been developed, such as those described in ISO 13437. As in other fields of engineering, confidence in the durability of geosynthetics is developing as the technology matures and the results of long-term service experience accumulate. Examples of experience to date are described in Clause 6.

4.3 Design life

The design life is specified on the time axis (Item 2 in Figure 1, Item 10 in Figure 2). It is set by the client (or a design code) and is decided at the design stage. Codes generally propose several fixed durations, according to whether the structure is meant for short-term use (typically a few years and not exceeding five years), temporary use (generally less than 25 years) or permanent use (over 25 years, and generally 50 to >100 years). The nature of the structure, the environmental risk involved and the consequences of failure may influence this duration (example: 70 years for a wall, 100 years for an abutment and beyond 100 years for landfills). Many geosynthetics have a temporary function although the structure is permanent; for example, an embankment over a weak soil may require a geotextile or geogrid reinforcement until the embankment has settled.

4.4 Margin of safety

At the end of the anticipated design life, the designer has to ensure a certain margin of safety (generally also indicated by codes), such that failure (Item 11 in Figure 2) is predicted to be well beyond the design life (Item 10). Item 3, the difference between the predicted available property and the predicted required property, represents the margin of safety for that component. This can be expressed as a ratio. The ratio can also be expressed in terms of the time to reach the end of life if the geosynthetic were to be left in service after the end of its design life (Item 5). These two representations of safety, the ratio of required and available property at the design life, and the ratio of the predicted end of life to design life, should be considered together because, in combination, they give a better idea of the real level of safety that exists.

The calculation of reduction factors for soil reinforcement applications is described in ISO/TR 20432.

4.5 End of life (function)

The end of life is the point on the time axis where the available property curve meets the required property curve (Item 11 in Figure 2). At this point, the product is predicted not to fulfil its function. Residual service may remain either if the expected loads are overestimated, or if they imply a combination of degradation mechanisms that may not all have reached their maximum values. Whatever the case, beyond that point on the graph, the possibility of end of function or failure is high.

4.6 Durability study

The design and durability assessment of a structure using a geosynthetic can be summarized as follows:

- defining the function(s) of the geosynthetic;
- making the inventory of the constraints imposed by the application (environmental, physical, chemical);
- defining the design life of the geosynthetic;
- quantifying the required properties of the geosynthetic (e.g. strength, permeability, impermeability, seam integrity);
- defining the geosynthetic properties;
- making sure that the estimated available properties at the end of the design life are greater than the required properties.

5 Constituents of geosynthetics

5.1 Types of geosynthetic

5.1.1 Polymeric durability considerations

The durability of a polymeric geosynthetic depends upon the unit weight, the formulation from which it is made, on any additives and fillers compounded with it, on the polymer microstructure, the fibre geometry and fabric layout for geotextiles, the unit weight, and thickness of geosynthetic barriers, and the quality of joints and junctions. The geosynthetic should be chemically and biologically resistant if it is to be suitable for long-term applications.

The polymers used to manufacture geosynthetics are generally thermoplastic materials which may be amorphous or semi-crystalline. An amorphous polymer has a randomly coiled structure which, at the glass transition temperature, t_g, undergoes significant change from a stiff, glassy, brittle response to loads below the glass transition temperature to a more ductile, rubbery response above t_g. Most polymers used in geotextiles are semi-crystalline, that is they contain small, more or less oriented crystallites, alternating with amorphous material. Since the change in behaviour only affects the amorphous regions, the glass transition is less marked for a semi-crystalline polymer. At a higher temperature, however, the crystallites melt, which produces an abrupt change in properties. Values of t_g and melting temperature are given in Table 1 for the polymers most commonly used in geosynthetics. In civil engineering applications, polyesters are used below their t_g while polypropylene and polyethylene are used above t_g. Any acceleration of laboratory tests crossing a transition, such as t_g, should be avoided or, if this is not possible, an appropriate factor of safety should be applied.

Mechanical drawing of polymers, e.g. for forming tapes, fibres or filaments, leads to increased orientation that results in higher tensile properties, improved durability and reduction of the changes in properties at the glass transition temperature. As the molecules become more oriented, the fibres become stronger. The crystallites are retained and the ratio of crystalline regions and amorphous regions should be properly balanced to produce the physical properties necessary for fibres used in geotextiles, or for the ribs of extruded geogrids (see 5.1.5). The increased orientation and associated higher density leads to higher environmental resistance. The durability assessment should consider whether any change in this morphology is likely during the service life of the product, and whether such a change will lead to a significant change in properties. Thermal analysis techniques have proved useful in measuring such changes.

Any polymer, whether amorphous or semi-crystalline, consists of long-chain molecules (macromolecules), each containing many chemical units. Each unit may be composed of one or more monomers, the number of which determines the length of the polymeric chain and resulting molecular weight. The nature and the number of the monomer distribution determine the length and structure of the polymeric chain. These factors can affect physical properties such as the tensile strength and modulus, impact strength, flexibility and heat resistance, as well as the durability properties. The mechanical and physical properties of the plastics are also influenced by the bonds within and between chains, chain branching, and the degree of crystallinity.

Crystallinity has a strong effect on polymer properties, especially the mechanical properties, because the tightly packed molecules within the crystallites result in dense regions with high intermolecular cohesion and higher resistance to penetration by chemicals. An increase in the degree of crystallinity leads directly to an increase in rigidity and yield or tensile strength, hardness and softening point, and to a decrease in liquid permeability and gas diffusion.

Durability of all geosynthetics is influenced by fibre or rib diameter or surface-to-volume ratio. Resistance to oxidation and UV exposure is generally dependent on fibre or rib diameter or thickness since the rate of oxidative/photo-oxidative reactions is often limited by the rate of diffusion of oxygen, especially at elevated testing temperatures. Evaporation and extraction of additives is also inversely related to surface-to-volume ratio. These factors should be taken into account in the design of suitable testing procedures and in considering the results of established tests. The choice of test method should ensure that oxygen availability has been simulated correctly. Changes of polymer morphology caused by testing at too high temperatures should be avoided.

Durability is further influenced by the nature and quality of the additives and fillers used.

5.1.2 Geotextiles

A geotextile is a planar, permeable, polymeric (synthetic or natural) textile material, which may be woven, knitted or non-woven. The principal materials used are polypropylene (PP), polyester (PET) and polyethylene (PE).

5.1.3 Geosynthetic barriers or polymeric and bituminous geosynthetic barriers

A geosynthetic barrier is a planar, relatively impermeable, polymeric (synthetic or natural) (GBR-P) or bituminous (GBR-B) sheet. The polymers used to manufacture the geosynthetic barriers are generally thermoplastic materials, elastomeric materials and modified bituminous materials. The materials used are high-density polyethylene (PE-HD), linear low-density polyethylene (PE-LLD), flexible polyvinyl chloride (PVC-P), flexible polypropylene (fPP), ethylene propylene diene monomer (EPDM), ethylene interpolymer alloy (EIA), chlorinated polyethylene (CPE), chlorosulfonated polyethylene (CSPE) and other elastomeric materials.

5.1.4 GBR-C

A geosynthetic clay barrier or liner (GBR-C) is a factory-manufactured geosynthetic hydraulic barrier consisting of clay, bentonite or other very low-permeability material supported by geotextiles, geosynthetic barriers, or a combination thereof, and held together by needle punching, stitching, chemical adhesives or other methods. Its durability is governed by the durability of the geosynthetics, the needle-punching fibres, the stitch-bonding filaments/yarns, the glues, and also the ion exchange between the material and the liquid retained or contained, and also desiccation.

5.1.5 Geoblankets (GBL)

A permeable structure of loose natural and/or synthetic fibres and other elements (natural or synthetic) bonded together to form a continuous sheet.

5.1.6 Geogrids

A geogrid is a geosynthetic formed by a regular open network of integrally connected elements with apertures to allow interlocking with surrounding soil, rock, earth, and other surrounding materials to function primarily as reinforcement and stabilisation. The elements in the machine and cross-directions may be integral or may be linked by bonding or interlacing. The manufacturing techniques vary widely. Currently weaving, knitting, extrusion and welding are used. Some products make use of fibres of polyethylene (PE), polypropylene (PP), polyester (PET), polyvinyl alcohol (PVA) and aramid. Coating materials include acrylic polymers, flexible polyvinyl chloride (PVC-P), and polyethylene (PE). In addition, PE and PP geogrids are made by the stretching of punched sheet.

5.1.7 Geonets

A geonet is an open planar, polymeric structure consisting of a regular dense network whose constituent elements are linked by knots or extrusions and whose openings are larger than the constituents. The polymers used to manufacture the geonet are generally thermoplastic materials, such as high-density polyethylene (PE-HD).

5.1.8 Geocells

A geocell is a three-dimensional, permeable, natural, or synthetic polymeric honeycomb or web structure, made of linked strips of geotextiles, geogrids, perforated sheets or geosynthetic barriers.

5.1.9 Geomats

A geomat is a three-dimensional, permeable, natural, or synthetic polymeric structure, made of bonded filaments, used to reinforce roots of grass and small plants and extend the erosion-control limits of vegetation for permanent erosion-control applications. The polymers used to manufacture the geomats are generally thermoplastic materials, such as PA, PE, PET and PP.

5.1.10 Geocomposites

A geocomposite is a manufactured or assembled material using at least one geosynthetic products among its components.

5.1.11 Geofoam

A geofoam is a block or a planar section of rigid cellular-foam polymeric material used in geotechnical engineering applications. Geofoam is commonly used as a lightweight fill to take up differential thermal expansion and for use in frozen ground.

5.1.12 Geospacers

Cuspated foils produced from extruded laminates, which are profiled during production into wave-shaped or truncated cuspate cone profiles, on one or both faces. They are typically made of polypropylene (PP) or high density polyethylene (HDPE).

5.2 Individual polymer types

5.2.1 General

The polymers used in geosynthetics are described below and three of their most important physical properties are listed in Table 1. The general remarks in 5.1.1 apply.

5.2.2 Polypropylene (PP)

Polypropylene is a thermoplastic polymer. PP is normally used in the isotactic stereoregular form, in which propylene monomers are attached in head-to-tail fashion and the methyl groups are aligned on the same side of the polymer backbone. PP has a semi-crystalline structure which gives it high stiffness, good tensile properties and resistance to acids, alkalis and most solvents. The tertiary carbon is sensitive to oxidation, so that stabilizers are added to prevent oxidation during manufacture, as well as to improve long-term durability and UV stability.

5.2.3 Flexible polypropylene (fPP)

Flexible polypropylene is a copolymer of propylene and ethylene. It is different from other PP-based olefinic polymers in that it is not a blend, but a reactor product using a proprietary catalyst. Its characteristics are quite different from the homopolymer PP and can be modified over a wide range by adjustment of the type, quantity and position of the second monomer in the molecular chain. In addition to the significantly higher degree of flexibility, it has a broad melting transition, which allows it to be thermally seamed over a wide range of seaming equipment. fPP maintains the inherent characteristics of polypropylene but is highly amorphous, so that greater attention needs to be paid to oxidation and UV stabilization.

5.2.4 Polyethylene (PE)

Polyethylene as used in geotextiles, geogrids and geosynthetic barriers is an alpha-olefin copolymer. It is used as high-density polyethylene (PE-HD), which is known for its good chemical resistance, or in its linear low-density form (PE-LLD), which is known for its excellent pliability, ease of processing and good physical properties, but which is less chemically resistant. PE requires to be stabilized to increase its resistance to weathering and oxidation. Certain grades of HDPE can be susceptible to environmental stress cracking. Their t_g being lower than −80 °C, it may be subjected to dimensional changes according to their formulation and structure.

5.2.5 Polyesters (i.e. PET, PEN)

Polyesters are a group of polymers. The type used most frequently in geotextiles is polyethylene terephthalate (PET) which is a condensation polymer of a dibasic acid and a di-alcohol. Since it is used below its t_g and in a highly oriented form, PET offers good mechanical properties, including a low creep-strain rate, and good chemical resistance to most acids and many solvents. The ester group, the important polymeric link, hydrolyses slowly in presence of water and throughout the fibre (“internal hydrolysis”). Under highly alkaline conditions there is an additional, more rapid surface reaction (“external hydrolysis”) which is particularly serious for fine fibres with a large surface-to-volume ratio, except when the fibres are coated. Polyethylene naphthalate (PEN) is less prone to hydrolysis than PET, but more sensitive to weathering.

5.2.6 Flexible polyvinyl chloride (PVC-P)

Flexible polyvinyl chloride is the most significant commercial member of the family of vinyl-based resins. PVC_P is a very versatile plastic because its blending capability with plasticizers and other additives allows it to take up a great variety of forms. Plasticizers and fillers are used in quantities of up to 35 % to create more flexible compounds, the choice of plasticizer being dictated by the properties desired. Conversely, PVC-P absorbs certain organic liquids which have a similar plasticizing effect. Since plasticizer depletion is the main degradation process of PVC-P, contact with polyethylene or other attractors should be avoided.. Thus, the choice of plasticizers is linked to the PVC-P durability. PVC-P also tends to become brittle and darken when exposed to ultraviolet light or heat-induced degradation through plasticizer depletion. Many PVC-P formulations, with quite different durability characteristics, are available on the market to suit specific applications. UV and oxidation stability can be adjusted to the application by the addition of suitable stabilizers.

5.2.7 Polyamides (PA)

Polyamides (PA, PA 6 and PA 6,6) are melt processable thermoplastics that contain an amide group as a recurring part of the chain. PA offers a combination of properties including ductility, wear and abrasion resistance, low frictional properties, low permeability by gases and hydrocarbons, and good chemical resistance. Its limitations include a tendency to absorb moisture, with resulting changes in dimensional and mechanical properties, and limited resistance to acids, oxidation and weathering. The PA fibres used in geotextiles have a t_g of 40 °C to 60 °C which is lowered through moisture absorption. UV and oxidation stability can be adjusted to the application by the addition of suitable stabilizers.

5.2.8 Ethylene propylene diene monomer (EPDM)

Ethylene propylene diene monomer is an elastomer composed principally of saturated polymeric chains constituted of ethylene and propylene molecules. This polymeric material presents a structure increasing resistance to ozone and ageing. The presence of a third monomer, ethylidene norbornene (ENB), is efficient at providing chemically active cure sites for vulcanization. Carbon black is added to the formulation to increase the UV resistance and also resistance to tear. Stabilizers are also added to the formulation prior to the vulcanization process to improve oxidation resistance.

5.2.9 Ethylene interpolymer alloy (EIA)

Ethylene interpolymer alloy describes a compound which derives its performance from the ketone ethylene ester (KEE) resin. The KEE resin typically makes up approximately 50 % of the polymer content of the EIA compound. Along with the ethylene backbone, two monomers are polymerized together: an ester such as vinyl acetate or *n*-butyl acrylate; and a ketone or a carboxyl group. UV and oxidation stability can be adjusted to the application by the addition of suitable stabilizers.

5.2.10 Chlorinated polyethylene (CPE)

Chlorinated polyethylene is a product one step away from PE. On the CPE molecule, chlorine atoms have been introduced along the side of the PE backbone, replacing hydrogen atoms. The much bulkier chlorine atoms tend to disrupt the formation of any crystallinity. The amount of chlorine that is introduced, and the randomness of their attachment, will determine the extent to which the resulting resin will be non-crystalline, or amorphous. Therefore, CPE will tend to be a more flexible material than polyethylene. UV and oxidation stability can be adjusted to application by addition of suitable stabilizers.

5.2.11 Chlorosulfonated polyethylene (CSPE)

Chlorosulfonated polyethylene is a family of synthetic rubber materials. It was introduced in the early 1950s as a synthetic rubber material with better ageing characteristics than the natural and styrene-butadiene rubbers. This improved rubber material is cross-linked to provide elasticity (which improves over time) and contains a minimum level of crystallinity to provide flexibility while maintaining strength. The basic polymer backbone is the same as polyethylene and, because there are no double bonds, the long polymer chains are relatively impervious to attack from degrading agents, such as oxygen, ozone or energy in the form of UV light. Chlorine atoms are introduced along the side of the PE backbone, together with a certain number of sulfonyl chloride groups. Since the sulfonyl chloride groups are larger than the chlorine atom, they are more efficient at breaking up the crystallinity and provide chemically active cure sites. Repair or extension is problematic due to its cross-linked nature. UV and oxidation stability can be adjusted to application by addition of suitable stabilizers.

5.2.12 Bitumen

Bitumen comprises modified bitumen (MB) and oxidized bitumen.

Modified bitumen (MB) is a modification of bitumen with a synthetic elastomer, for example styrene-butadiene-styrene (SBS). The polymers present in a formulation typically increase the elasticity, fatigue resistance and ageing of the bitumen. Sensitivity to UV and oxidation can be adjusted by suitable additives.

Oxidized bitumen has no modification and has different ageing properties to those of modified bitumen.

5.2.13 Aramid

Aramid is a synthetic fibre, in which the fibre-forming substance is a long-chain synthetic polyamide, in which at least 85 % of the amide linkages are attached directly to two aromatic rings. The links are formed by strong hydrogen bonds.

Aramid offers a high strength-to-weight ratio and exhibits low elongation and low creep deformation. It is typically stable between pH 4 and 9,5.

Aramid is generally sensitive to UV radiation. The amide bonds can be hydrolized especially in more acid media. The material absorbs moisture and has a low abrasion resistance. Aramid has high glass transition and dissociation temperatures.

5.2.14 Polyvinyl alcohol (PVAL)

After synthesis, polyvinyl alcohol is obtained in the form of a white precipitate, which is then refined and washed to produce the powdered commercial product. The water insoluble PVAL used in geosynthetics is generally formed into fibres by means of three successive operations: dissolution, spinning and finishing. The resulting fibres exhibit a very high tenacity, high modulus and low elongation (typically <6 %). PVAL is unaffected by animal, vegetable and mineral oils and exhibits a high degree of resistance to acids and alkalis. It is typically stable between pH 4 and 13.

5.2.15 Polystyrene (PS)

Polystyrene is mainly used in extruded form (XPS) or as an expanded foam (EPS). UV and oxidation stability can be adjusted according to the application by the addition of suitable stabilizers.

5.2.16 Typical physical properties of polymeric geosynthetics

Table 1 — Typical physical properties of polymeric geosynthetics

Polymer	Density of blended polymer g/cm³	Melting temperature[a] °C	Glass transition temperature[a] °C
PP	0,900 to 0,910	170	<–10
fPP	0,89	150	<–20
PE-HD	0,939 to 0,960	130	<–80
PE-LLD	0,910 to 0,925	120	<–80
PET	1,38 to 1,40	250	80
PVC-P	1,3 to 1,5	N/A	–25 to 100
PA 6	1,2	220	50
EPDM	1,40	NA	–60
CPE	1,2	170	<–50
CSPE	1,47	NA	–55
MB	1,2 to 1,3	NA	–50 – 100
Aramid	1,44	550	300
PVAL	1,2 to 1,3	228	85

[a] Approximate temperatures are given. Specific temperatures are dependent on polymer properties, such as molecular weight, percentage crystallinity, orientation of crystallites and formulation ingredients such as additives and fillers. The values of t_g are derived from DSC measurements. The values of t_g for the very slow processes relevant for durability are generally markedly lower than those measured using DSC, example values of t_g lower than 60 °C have been observed while DSC gives 80 °C. For the purposes of durability assessment, values of t_g measured by DTMA are preferred, if available.

Table 1 *(continued)*

Polymer	Density of blended polymer g/cm^3	Melting temperature[a] °C	Glass transition temperature[a] °C
PS	1,05 (solid material)	230	100

[a] Approximate temperatures are given. Specific temperatures are dependent on polymer properties, such as molecular weight, percentage crystallinity, orientation of crystallites and formulation ingredients such as additives and fillers. The values of t_g are derived from DSC measurements. The values of t_g for the very slow processes relevant for durability are generally markedly lower than those measured using DSC, example values of t_g lower than 60 °C have been observed while DSC gives 80 °C. For the purposes of durability assessment, values of t_g measured by DTMA are preferred, if available.

5.3 Manufacturing process

5.3.1 General

Geosynthetics are manufactured using several different processes which are described in this subclause.

5.3.2 Geotextiles

5.3.2.1 General

Geotextiles include non-woven, woven and knitted products. All are made of polymers drawn into fibres, yarns or films. The different manufacturing processes lead to geotextile products with a wide range of properties.

The drawing process is very important in the production of the different types of polymeric fibres, filaments and tapes. During this process, the polymeric chains become aligned along the filament or tape length and their crystallinity, mechanical properties and durability all increase. The mechanical properties of the product depend upon the details of the manufacturing process.

The structure of the fabric and the fibre diameter will contribute to the durability properties; for example, large diameter fibres and thick tapes are less susceptible to weathering. The stabilization systems applied to improve the properties are therefore adjusted to suit either a non-woven geotextile of finer fibres, a woven geotextile or a geogrid.

5.3.2.2 Non-woven geotextiles

For the production of non-woven geotextiles, continuous filaments (spunbonded) or staple fibres (cut fibres) are used. Woven and knitted geotextiles are produced using different types of yarn, such as spun yarns, multifilament yarns, monofilaments and film tapes or split film yarns.

The types of fibres, multifilaments, monofilaments and tapes used in the manufacture of such geotextiles are produced mainly by a melt spinning process. To produce fibres, multifilaments and monofilaments the molten polymer is extruded through orifices of a die, cooled, drawn by stretching and, according to the end use,

a) laid on a screen to form a planar structure (continuous filament or spunbonded non-woven),

b) processed to staple fibres by crimping and staple cutting, or

c) processed to multifilaments or monofilaments, winding the filaments after drawing and annealing directly on to spools. In the case of multifilament production, this technique is known as spin-drawing.

Spunbonded non-wovens (continuous filament non-wovens) are manufactured in a continuous process starting with the polymer and proceeding through filament production, geotextile formation and filament bonding in the same line, finishing with the roll of non-woven.

Staple fibre non-wovens are manufactured in a two-stage process: the first stage consists of fibre production (extrusion and cutting) and the second stage consists of the formation of the geotextile, bonding and production of the finished roll.

Bonding of non-woven geotextiles formed from either continuous filaments or from staple fibres is done mechanically by needle punching with felting needles, by thermal (cohesive) bonding using heat with or without pressure (calendering), by chemical (adhesive) bonding, or by a combination of these processes.

The physical structure and properties of the non-woven products are often related to the bonding system. More specifically, heat-bonded wovens and non-wovens (tape-film wovens) are thin products, in which the fibres are oriented in a two-dimensional structure. Needle-punched non-wovens have a three-dimensional structure, the configuration of which may be fixed by a final thermal bonding stage.

5.3.2.3 Woven and knitted geotextiles

Woven geotextiles are also produced in a discontinuous process with at least two stages. The first stage is the production of the yarn, monofilament or multifilament. The second stage is the weaving either to flat wovens (or simply wovens) or knitted wovens (knits).

Weaving involves the interlacing of two sets of yarns at right angles to each other: the machine (MD) and cross-machine direction (CMD). The MD threads are held under tension and in distance by means of a loom. The loom is equipped with MD threads passing through heddles on two or more shafts. The MD threads are moved up or down, depending on the design by the shafts, creating a space called the shed. The CMD yarn is brought into the shed, perpendicular to the MD yarn. The raising/lowering sequence of MD threads gives rise to many possible weave structures. The number of threads per unit width and their individual strength lead to final product strength.

In the knitting process, yarn bundles are tensioned parallel in the machine direction (MD) and perpendicular yarns are placed in the cross-machine direction (CMD). An extra thread is used to link these together and to form a stable integral mesh. Usually a coating is applied in order to provide protection.

Film tapes and split yarns are normally only produced from polypropylene and polyethylene. These products are made by extruding a film, cutting the film into individual tapes and stretching them by a uniaxial drawing process followed by thermal fixation. Coarse film tapes may be too stiff for further handling in beaming and weaving, and are therefore fibrillated after the drawing process and before winding and twisting. These types of yarn are then called split film yarns. Nevertheless, large volumes of geosynthetics are woven directly from film tapes.

5.3.3 Geosynthetic barriers

Geosynthetic barrier sheets are normally produced from thermoplastic polymers. These products are made by extruding a sheet or by blown film processes or by calendaring.

The manufacturing begins with the production of the raw materials which include the polymer resin, various additives, fillers and lubricants. The formulations are then processed into a geosynthetic barrier sheet of various width and thickness by one of two extrusion methods. In the first process, called flat die, the polymer formulation is forced between two horizontal die lips. The second process, called blown film, uses a circular die which forces the polymer formulation between two concentric die lips oriented vertically. The polymer exits the die and extends upward in the form of a cylinder. At the top of the system, two counter-rotating rollers draw the cylinder upward and, after passing over the rollers, the sheet is longitudinally cut, unfolded to its full width, and rolled onto a roll.

The mechanical and durability properties of the product are related to the details of the manufacturing process as well as to the bonding of the sheets.

Bonding of geosynthetic barrier sheets is done mechanically by thermal (cohesive) bonding using heat with or without pressure, by fusion using heating elements (hot wedges) with pressure, by chemical (adhesive) bonding, or by a combination of these processes.

The continuous process used to produce bituminous geosynthetic barriers is quite different. A geotextile is unrolled and dipped into consecutive baths containing a modified (MB) bituminous formulation to obtain a bitumen-impregnated geotextile product.

All flexible and scrim-reinforced geosynthetic barriers made from PVC-P and CSPE are manufactured by a calendering method. The polymer formulation is fed to a mixer from which the material exits, moves on a conveyer to a roll mill and passes through a set of counter-rotating rollers (calendar) to form a final sheet. This type of manufacturing gives rise to multiple plies of laminated geosynthetic barriers with an open-weave fabric (called scrim) between the individual plies.

5.3.4 Geogrids

Geogrids are planar, polymeric structure consisting of a regular open network of integrally connected, tensile elements, which may be linked by extrusion, bonding, or interlooping or interlacing, whose openings are larger than the constituents.

5.3.5 Geonets

Geonets are typically manufactured by an extrusion process, in which a minimum of two sets of strands (filaments) are overlaid to yield a three-dimensional product. The openings between the strands permit an in-plane flow of liquids, such as water or landfill leachate, and gases.

5.3.6 Geocomposites

Geocomposites are composed of two products including at least one geosynthetic joined together by a process such as bonding, gluing, welding, weaving, knitting or sewing.

5.3.7 Geocells

Geocells are three-dimensional geosynthetics used for soil confinement in erosion-control applications. They are manufactured either by extrusion, polymeric strip welding or geotextile strip welding or stitching.

5.3.8 GBR-C

A clay geosynthetic barrier (GBR-C) is a factory-manufactured geosynthetic hydraulic barrier consisting of clay supported by geotextiles, geosynthetic barriers, or a combination thereof, that are held together by needle punching, stitching, chemical adhesives or other methods.

5.4 Recycled and reworked materials

In the industry, three expressions are used to identify recycling of processed materials:

- reworked material (RWM) (or regrind);
- post-consumer material (PCM);
- post-industrial material (PIM).

It is common practice within the plastics industry to recycle the processed material (in-house rework resin), since it can be considered comparable to virgin material.

When the resin comes from the same industrial process and same product, the reworked material (RWM) is reclaimed within the same process that generated. It may be used after regrinding without quantity limitations, or after pelletizing but limited to 10 % without further proof.

Pelletizing is a thermal process whereby the polymer melt coming from an extruder is pressed through a die plate and cut by knives to make pellets. This process may affect the properties of the product. If more than 10 % of pelletized RWM is used, evidence of durability shall be given.

The use of PCM or PIM may compromise the durability of geosynthetics. It is advisable not to use these materials without proof of their long-term durability. The composition of the blended polymer should be assured. Also, no post-industrial recycled polymer shall be added to the geosynthetic barrier formulation.

Recycled materials may originate from various stages of processing following their original formulation, or from subsequent processes such as weaving for geotextiles. The materials may have been used in service, whether in the form of textiles or as other products such as packaging. The level of control over the quality of the material, and thus its durability, decreases with the number of stages and processes it has gone through after leaving the original manufacturer's plant.

5.5 Additives, stabilizers, fillers and reinforcement scrims

5.5.1 General

Additives play a major role in polymer stabilization. Typical additives used in the production of geosynthetics are antioxidants, acid scavengers, metal ion deactivators, UV stabilizers, lubricants, plasticizers, lubricants, mineral fillers and scrims.

5.5.2 Antioxidants

Antioxidants prevent deterioration of the appearance and of the physical properties of polymers caused by the oxidative degradation of polymer bonds. Stabilization is achieved by either providing alternative opportunities for termination reactions, or by preventing the formation of free radicals and thus interrupting the chain of reaction. With some stabilizers, the oxidation of the polymer starts only after an induction (or incubation) period has elapsed. During this time, the stabilizer is consumed causing a strong inhibition of polymer oxidation. With other antioxidants, no induction period but a reduced velocity of oxidation is achieved. Both types of action may be combined by mixtures of different antioxidants or by certain single antioxidants.

Oxidation is accelerated by the heat generated during the manufacturing process. These antioxidants, designed to work during the manufacturing process (high temperatures), are referred to as processing antioxidants. The main groups are hindered phenols and organic phosphites.

Antioxidants intended to protect the geosynthetic during its subsequent exposure to the environment (low temperatures) are referred to as long-term antioxidants. The main groups are aromatic amines, thioesters, hindered phenols and hindered amines.

5.5.3 Acid scavengers

Acid scavengers provide protection of the polymer to acids resulting from catalyser residues or oxidation/hydrolysing processes in the polymer. They are considered to be a part of the stabilizer package along with primary antioxidants and phosphites. They are mainly soluble or dispersible bases, e.g. metallic stearates, lactates, hydrotalcites or zinc oxides.

5.5.4 Metal ion deactivators

Heavy metal ions, including transition metal ions, catalyse the decomposition of peroxides, leading to the formation of reactive radicals which accelerate autoxidation. Ion deactivators form stable inert complexes with such ions, and thus may contribute considerably to stabilization.

5.5.5 UV stabilizers

UV stabilizers provide ultraviolet light stabilization to polymers by several mechanisms that interfere with the physical and chemical processes of light-induced degradation in the presence of oxygen (photo-oxidation):

- absorbing the range of critical wavelengths by UV-absorbing chemical compounds (e.g. hydroxybenzophenones) or pigments (e.g. carbon black or titanium dioxide);
- quenching of energized photochemical states by certain quenchers (e.g. certain nickel compounds);
- trapping of free radicals by certain antioxidants [e.g. hindered amine light stabilizers (HALS)].

Often a combination of different stabilizers provides the best protection.

5.5.6 Plasticizers

In order to make a flexible compound from a rigid resin, such as PVC-P, plasticizers must be added. They come in a variety of chemical compositions and molecular weights. The plasticizing additives, such as those containing residual fatty acids (glycerol esters, laureates, oleates, phthalates and stearates), have to be resistant to migration and leaching and may have to be protected with other additives since they are susceptible to attack by micro-organisms.

5.5.7 Lubricants

Process aids can include materials, such as waxes, stearates or low-molecular-weight polyethylenes. These materials assist in the production of a calendered sheet material, and subsequent handling of a geosynthetic. These products provide improved mill and calender roll release at production temperatures, and improved anti-blocking properties of the geosynthetics.

5.5.8 Mineral fillers

Mineral fillers, such as clay and calcium carbonate, are usually added to the formulation for economic considerations. They can provide some internal reinforcement for the compound, while increasing the compound strength.

5.5.9 Scrims

A scrim is usually an open-weave polyester fabric inserted between the individual plies of a geosynthetic barrier. It is used to reinforce a flexible product. Generally, scrims are made of 1 000 dtex filaments spaced at 0,1 mm (specified as 10 × 10, 1 000 dtex).

6 Environmental factors that may lead to degradation

6.1 The environment above ground

Ageing of exposed geosynthetics is mainly initiated by the ultraviolet (UV) component of solar radiation, heat and oxygen, with contributions from other climatic factors, such as humidity, rain, oxides of nitrogen and sulfur, ozone, deposits from polluted air and pollens, and contained liquids.

The energy of ultraviolet radiation is sufficient to initiate rupture of the bonds within the polymer leading to subsequent recombination with, for example, oxygen in the air, or initiating more complex chain reactions. This is a general property of polymers and is not restricted to geosynthetics. Additives increase resistance to ultraviolet radiation in a variety of ways as described in 5.5.

The resistance to ultraviolet radiation is affected both by the surface temperature of the sample and by precipitation, for which reason accelerated weathering tests include control of temperature and an intermittent spray cycle. Since natural weathering is both seasonal and variable, artificial tests have the advantage not only of being able to increase the intensity of the radiation, but also of ensuring that the radiation is constant, controlled and lasts up to 24 h a day. The performance following accelerated testing is related to the duration of exposure on site as described in 8.3.1.

In most applications, geosynthetics are exposed to UV light for only a limited time during storage, transport and installation and are subsequently protected by a layer of soil. On the other hand, exposed geosynthetic barriers, mainly installed at the top of slopes of reservoirs, ponds and channels, must resist for a longer time. The need for either short- or long-term resistance to weathering therefore depends on the application.

Exposure to UV has been shown to reduce the subsequent chemical resistance of thin textiles but this has not been observed in geotextiles. In addition, atmospheric pollution and acid rain may enhance UV degradation, particularly of PA, for longer exposures above ground. Attacks by birds and animals have been observed during deliberate exposure of specimens during outdoor weathering tests and in applications.

6.2 The environment below ground

Below ground the main factors affecting the durability of geosynthetics are as follows. They apply especially to the soil particles, soil suspension and soil water in direct contact with the geosynthetic:

- particle size distribution and angularity;
- acidity/alkalinity (pH);
- metal ions present;
- presence of oxygen;
- moisture content;
- organic content (e.g. phenols, organic acids);
- temperature;
- micro-organisms.

Adequate specification of the soil is thus essential for proper consideration of the durability of the geosynthetic.

Soils as encountered in the world should be divided into topsoil (0,20 m to 1,00 m) and underlying sediments. Their nature depends primarily on the underlying rock and on the local climate, including the mean temperature and the drainage conditions. Topsoil is a mix of weathered sediments and humus produced by decaying organic material. The conditions of decay can be aerobic, with oxygen present, or anaerobic.

Sediments are deposits of minerals and lack organic material. They are generally formed by the physical and chemical weathering of rocks. Silt, sand and gravel (particle size 0,002 mm to 60 mm) are formed by physical weathering, while clays (particle size <0,002 mm) are formed by chemical weathering. Fills and backfills originate from sediments, where particle size and angularity is determined not only by the manner in which the sediment was formed but also by any subsequent industrial processing such as crushing. The range of particle sizes of a soil is measured by sieving and is depicted by a graph of particle size against percentage by weight. Mechanical damage increases with particle size, and with the angularity of the particles. This is described further in 6.4.4. Sharp-edged particles in underdrain and drainage layers can cause considerable mechanical damage to geosynthetics; in fact the exhumation of specimens after a number of years and leak detection surveys on covered geosynthetic barriers often shows that puncture is the only form of degradation that can be identified with certainty.

The topsoil or sediments can be fully saturated, partially saturated or dry, or intermittently wet and dry. In wetter climates, the drainage is principally downwards, drawing soluble materials to lower levels, while in drier climates, moisture is removed by evaporation at the surface and the resultant upward movement of the water draws these soluble fractions upwards and deposits them at the surface. The water content of an unsaturated soil is described by the local relative humidity.

The temperature of the soil is constant (to within ±0,5 °C) only at a depth of 10 m or more. Its value is then equal to the annual average atmospheric temperature at the surface. Daily and seasonal variations occur with decreasing intensity as the distance from the surface increases. For example, the daily variation in atmospheric temperature and solar radiation is felt to a depth of 0,5 m (Segrestin and Jailloux, 1988) and even more in Nordic regions (1,2 m to 1,5 m). Since higher temperatures increase the rates of ageing and creep of polymers disproportionately, their effect on geosynthetic behaviour may need to be considered for material installed close to the surface.

Similarly, very cold temperatures increase the brittleness of the polymeric material. Special considerations apply to frozen ground or permafrost, where the combined effect of frozen soil and geosynthetic should be taken into account.

Topsoil generally has a pH of 5,5 to 7, but anaerobic peats or soils which have been affected by acid rain may have a pH of approximately 4. Atmospheric carbon dioxide leads to generally increased acidity at the surface. Limestone or chalk soils may have a pH of 8 to 8,5. Geological deposits have a wide range of pH, as shown in Table 2, with values between 2 and 10 having been recorded.

Table 2 — Some typical minerals and fills and their pH values

Mineral	Formula	Maximum pH
Feldspar		
Albite	$NaAlSi_3O_8$	9 to 10
Anorthite	$CaAl_2Si_2O_8$	8
Orthoclase	$KAlSi_3O_8$	8 to 9
Sand		
Quartz	SiO_2	7
Muscovite	$KAl_2(AlSiO_3)O_{10}(OH)_2$	7 to 8
Clays		
Kaolinite	$Al_2SiO_2O_5(OH)_4$	5 to 7
Carbonates		
Dolomite	$CaMg(CO_3)_2$	9 to 10
Calcite	$CaCO_3$	8 to 9

The use of bentonite and other clays in civil engineering construction, such as diaphragm wall construction, grouting processes, sealing layers in landfill and tunnelling, causes local alkaline areas of pH values of 8,5 to 10. If the soil is treated with lime (calcium hydroxide), then the possible pH can be as high as 11. Concrete substrates can also exhibit high alkalinity (pH 11 and higher).

6.3 Chemical and biological effects on a geosynthetic

6.3.1 General

Chemical attack is most serious when the polymer chain backbone is broken, leading directly to a loss of mechanical properties and, frequently, to a loss of hydraulic properties. Chemical degradation of polymers occurs by a variety of processes including oxidation and hydrolysis, depending on the type of polymer and on the acidity or alkalinity of the soil. Acidity and alkalinity are expressed as pH, a scale with neutral soil having a pH of 7, lower values implying acid soils and higher values alkaline soils.

All chemical reactions occur more rapidly at higher temperatures, as described by Arrhenius' Law (see 8.5.3.4).

6.3.2 Hydrolysis of PET and PA

Polyesters and polyamides are susceptible to hydrolysis, which in polyester materials takes two forms. The first, alkaline or external hydrolysis, occurs in alkaline soils above pH 9,0, particularly in the presence of calcium, and takes the form of surface attack or etching. Caution should be applied in the use of polyesters for long periods above pH 9. The second, internal hydrolysis, occurs in aqueous solutions or humid soil at all values of pH. It takes place throughout the cross-section of the material. The rate of hydrolysis is slow, such that the process has little effect at mean soil temperatures of 15 °C or below in neutral soils, although it can be accelerated in acids. The rate of internal hydrolysis in a partially saturated soil depends upon the local relative humidity. Sensitivity to hydrolysis can be reduced by selecting a polyester of sufficiently high molecular weight [i.e. high intrinsic viscosity (IV)]. It is recommended that the number-averaged molecular weight, M_n, should be greater than 25 000 and the carboxyl-end-group count less than 30 μeq/g.

6.3.3 Oxidation of PE and PP

Polypropylene and polyethylene are susceptible to oxidation, as are most other polymers. This is accelerated by the catalytic effects of transition metal ions in a chemically activated state at levels as low as 100 ppm (parts per million). Of these the ferric (Fe^{3+}) ion is the most common, but copper and manganese have also been shown to be important. However, the sensitivity to oxidation is dramatically reduced by the inclusion of antioxidant stabilizers or additives (see 5.5), and is retarded by the high level of orientation in polymer fibres or ribs as are found in most geotextiles and geogrids.

For UV radiation and oxidation with limited oxygen diffusion, the rates of degradation depend strongly on surface-to-volume ratio, as do the rates of extraction and evaporation of additives.

6.3.4 Biochemical attack

Biochemical attack occurs generally by means of oxido-reduction, depending on the type of polymer and on the biomass growth. The conditions of decay can be aerobic, with oxygen present, or anaerobic.

In the past 25 years, there have been no reports of microbial attack on synthetic geotextiles either in testing or in the ground. Only geotextiles containing vegetable fibres (most of which are deliberately designed to degrade once natural vegetation has become established) are likely to be affected. However, in topsoil, micro-organisms, such as bacteria and fungi, might attack geotextiles if they contain components that provide nutrition and if the micro-organisms can penetrate the remaining polymer. The long-chain molecules of thermoplastics used in geotextiles are generally resistant to microbial attack. Also, low molecular components and certain additives could be susceptible to biodegradation, but this can be countered by biostabilizers. Micro-organisms could, in theory, produce degradation products that attack geotextiles chemically. Soil burial tests (EN 12225 and ASTM D3083) endeavour to provide a soil of maximum biological activity to encourage any reaction that can occur, but it is not possible to accelerate the test further.

Geotextiles in soil also come into contact with animals such as rodents and with the roots of plants. Rodents can locally destroy a geotextile, while roots can penetrate and clog it. No specific tests have been proposed to simulate attack by rodents, while CEN/TS 14416 tests the susceptibility to penetration by roots.

6.3.5 Chemical effects on other geosynthetic barriers

PVC-P geosynthetic barriers have a high chemical resistance to the majority of acids, bases, salts and alcohols, but the plasticizers can be affected by benzene, trichloroethylene and toluene. The PVC-P structure can be attacked by ketones, such as methyl-ethyl-ketone, tetrahydrofuran and acetone. The effect is more critical in amorphous polymers such as PVC-P, where very small fractions of a chemical, often a subsidiary additive to a compound liquid, have been known to cause critical failures.

fPP geosynthetic barriers can be affected by oxygen (see 5.2.3) and by halogenated aliphatic hydrocarbons, aromatics and aliphatic hydrocarbons. Care must be ensured when in long-term contact with the following chemicals: organic acids, volatile organics, oils and waxes and strong oxidants.

CSPE and EPDM geosynthetic barriers can be affected by industrial-waste liquids containing high concentrations of aromatic and chlorinated organic hydrocarbons (see 5.2.8 and 5.2.11).

Bituminous geosynthetic barriers should not be contact with nonpolar solvents, aromatic solvents, aliphatics or halogenics for long periods of time, nor with very strong acidic and basic solutions (pH <2 and pH >9).

The sensitivity of geosynthetic barriers to microbiological attack is the same as for geotextiles.

EN 14414 describes a test for resistance of geosynthetic barriers to chemical attack in landfills, using both specified chemicals and synthetic leachates, while EN 14415 describes a test for the leaching of additives by chemicals, leaving the remaining polymer vulnerable to oxidative attack.

Table 3 lists the principal alternative test methods for geosynthetic barriers.

Table 3 — Geosynthetic barrier durability tests

Description	Standards	PVC	EPDM CSPE	fPP	PE	MB	GBR-C
Carbon black dispersion	ISO 18553				*		
Carbon black content	ISO 6964			*	*		
Stress-cracking resistance	EN 14576			*	*		
	ASTM D5397			*	*		
Oxidative induction time (DSC)	ASTM D5885		*	*	*		
	ISO 11357-6	*	*	*	*		
Resistance to weathering (UV)	ASTM D4355	*	*	*	*		*
	EN 12224	*	*	*	*	*	*
	ISO 4892-2	*	*	*	*	*	*
	ASTM G151		*				
	ASTM G154			*	*		
	ASTM G155			*	*		
	EN 1297-1	*	*	*	*	*	
Chemical resistance to liquids	ASTM D5747	*	*	*	*	*	
	ISO 175	*	*	*	*		
	EN 14030	*	*	*	*	*	*
	EN 14414	*	*	*	*	*	*
	EN 14415	*	*	*	*	*	*
Chemical immersion procedures	ASTM D5322	*	*	*	*	*	*
	ASTM D5496	*	*	*	*	*	*
Resistance to micro-organisms	EN 12225	*	*	*	*	*	*
	ASTM G160	*	*	*	*	*	*
Oxidation	ASTM D5721	*	*				*
	ISO 13438	*	*	*	*	*	*
	EN 14575	*	*	*	*	*	
Water absorption	ASTM D1239			*			
	ISO 62	*	*	*	*		
Plasticizer content and molecular weight	ASTM D2124						
Melt flow index	ISO 1133-1			*	*		
Softening point (ring and ball)	ASTM D36					*	
	EN 1427					*	
Loss of volatiles	ASTM D1203	*		*			

Table 3 *(continued)*

Description	Standards	PVC	EPDM CSPE	fPP	PE	MB	GBR-C
Swell index of clay	ASTM D5890						*
Evaluation of aged geosynthetic	EN 12226	*	*	*	*		

6.4 Effects of load and mechanical damage

6.4.1 Tensile load: Creep and creep-rupture

A major difference between polymers and metals is that, at normal operating temperatures and tensile loads, polymers extend with time, that is they creep. This is particularly important in the design of reinforced soil structures.

At high loads, creep leads ultimately to creep-rupture, also known as stress-rupture or static fatigue. The higher the applied load, the shorter the lifetime. The highest load which, if applied continuously over the lifetime of the product, is predicted to lead to creep-rupture on the day following the design life is defined as the unfactored design load. Of equal importance is definition of the creep strain, which even at low loads can cause a reinforced soil structure to reach a serviceability limit by movement or sagging without leading to total collapse. This can be predicted from isochronous curves (see ISO/TR 20432).

At the microscopic level, when a load is applied to a polymer it will cause the long-chain molecules to stretch or rearrange themselves. While the crystalline areas remain relatively stable under load, rearrangement takes place in the amorphous regions, and it is noticeable that in polymers, such as polyethylene and polypropylene used above t_g, where the amorphous regions are in a rubbery rather than a glassy state, creep takes place more rapidly and is more sensitive to temperature than those, such as polyester, used below t_g. In oriented polymers, an important part is played by the "tie" molecules which link one crystallite with another across the amorphous regions. For example, in polyester molecules, the load can cause these highly stressed molecules to change the arrangement of their side branches, resulting in a temporary reduction in secant modulus and in the characteristic S-shaped stress-strain curve. These processes of rearrangement continue under the combined effects of load and thermal activation.

Tensile creep for a geotextile is measured in accordance with ISO 13431, in which a specimen generally 200 mm wide is placed under a constant load for a set time, typically 1 000 h (six weeks) or 10 000 (1,14 years), and the elongation monitored. Such tests can be performed over a range of loads and, if required, at various temperatures (see ISO/TR 20432). In a reinforced soil structure, part of the load can in fact be transferred to the soil so that the creep measured in air represents a maximum or conservative value.

Creep-strain effects in polymeric geosynthetic barriers are not generally considered in design. Installation stresses in geosynthetic barriers can, however, diminish with time thanks to stress relaxation, the time-dependent reduction in stress at a constant strain, which is the counterpart of creep and which depends on the same parameters of strain and temperature. Creep-rupture, however, can be significant, because, in unoriented polymers such as polyethylene, the high energy, ductile failure that occurs at short times under high loads is preceded at lower loads by a low energy, "brittle" form of failure. Although this effect is well understood, it means that short-term tests cannot be used to predict long-term lifetimes, and leads to a "knee" in the creep-rupture characteristic. The susceptibility to creep-rupture can be reduced by the use of high molecular weight polymer, copolymerization and orientation. Long-term tests under load at high temperatures can be used as a proof test to ensure sufficient resistance to creep-rupture.

6.4.2 Synergy of tensile load with environmental effects (environmental stress cracking)

Environmental effects generally have little effect on creep strain but can reduce the creep-rupture lifetime. If the combined effect of load and environmental effect is greater than the addition of their individual effects, then there is said to be synergy between them.

Environmental stress cracking is the acceleration of low energy, “brittle” creep-rupture in unoriented polymers by fluids, particularly those which dissolve in and swell the polymer, enabling the molecules to untangle and separate. Semi-crystalline polymers such as polyethylene are susceptible to ESC, while oriented fibres and the ribs of drawn geogrids are resistant to it (Wrigley 1987).

Environmental stress cracking of geosynthetic barriers has been studied widely. Some fluids are chosen to accelerate crack growth deliberately in testing. Although modern grades of polyethylene can be very resistant to environmental stress cracking, it is equally necessary to control the presence of residual stresses in a geosynthetic barrier introduced during production, installation or welding, and to select material suited to the expected content of the leachate.

Susceptibility to stress cracking can be measured by immersing notched samples under load in a bath of liquid and can be accelerated by raising the load, liquid concentration or temperature (EN 14576; ASTM D5397). This provides a screening test for the selection of suitably resistant materials.

6.4.3 Effect of mechanical load on weathering and oxidation

Mechanical stress can have a significant effect on the rate of photo-oxidation and thermal oxidation of HDPE and PP, particularly in geosynthetic barriers.

6.4.4 Loading during installation: Mechanical damage

Mechanical damage is caused by direct contact between the soil fill or granular drainage layer and the geosynthetic under pressure. Light damage consists of scuffing, scratches on the surfaces and abrasion of the fibres, while more severe damage may include cuts, tears and perforations in the fabric or sheet. For geotextiles, sheaths or coatings may be cut away to reveal the fibres they protect. The surface of geosynthetics may be abraded, and oriented polymers may split along the direction of orientation. The susceptibility of some geosynthetics to mechanical damage during installation can increase under frost conditions. The severity of the damage increases with the coarseness and angularity of the granular material and with the applied compactive effort of equipment, and decreases with the thickness of the geosynthetic. Clays and sands ($d_{50} < 2$ mm) generally produce little mechanical damage.

Severe damage can be caused when backfill is dropped from a height onto a geosynthetic, particularly when large rocks or cement blocks are used for erosion control. More detail is given in Watn and Chew (2002). This damage may reduce the mechanical strength of the geosynthetic. When perforations are present, it will affect the hydraulic properties.

In general, the method of installation should preclude damage to the geosynthetic or provide a method for detection and remediation (e.g. leaks). Damage can be restricted by the choice of a suitable material or by inclusion of a protective layer. If, however, some damage is unavoidable, tests should be carried out if there is a risk that it could affect the performance of the geosynthetic. These tests should be carried out as performance tests, using the actual soil and equipment in accordance with accepted practice (ASTM D5818, for general guidance ISO 13437). ISO 10722 is an index test that should only be used for comparison of materials.

For reinforcement applications, a reduction factor should be applied to take into account the reduction in strength caused by the damage. More details are given in ISO/TR 20432.

6.4.5 Normal pressure: Compressive creep and penetration

Normal pressure can induce long-term deformation of geosythetics and can also force a material, such as a geonet, to embody into a soft material, such as a geosynthetic barrier, and reduce the distance of separation, restricting the drainage flow. Compressive creep strain and, if necessary, the time to collapse should be measured using EN 1897.

6.4.6 Abrasion and dynamic loading

Geosynthetics used under roads, railways or in coastal erosion protection may be subject to dynamic loading which will lead to mechanical damage to the geosynthetic in a manner similar to mechanical damage on the installation. While fibres and bulk thermoplastics are susceptible to mechanical fatigue, the principal cause of degradation is abrasion and frictional rubbing. The test for mechanical abrasion is given in ISO 13427 but there is no test for mechanical fatigue. Geosynthetics intended to operate under severe dynamic loading on the coarse backfill should therefore be subjected to performance tests which simulate or accentuate the site conditions. In railway applications, dynamic loading may apply only intermittently, giving a possibility of simulating a long service life.

7 Evidence of the durability of geosynthetics

7.1 Historical development

Large quantities of geotextiles made from man-made fibres were used in the Netherlands after the catastrophic flooding of 1953 which inundated 150 000 hectares and killed 2 000 people. To stop the flooding and reconstruct the sea barriers many million square metres of woven synthetic fabric were used, partly because at that time Europe had run out of jute for sandbags and willow fascines for seabed protection.

In the 1960s, a range of non-woven fabrics was manufactured for use as foundation, separation, and filter layers between granular fills and weak subsoils. In the 1970s, different grades of reinforcing materials, such as heavy wovens and extruded geogrids, were developed specially for such applications. The first applications of PE-HD geogrids, in retaining walls in the UK, were probably in the late 1970s. Flexible polyester-based woven geogrids were developed starting in 1984 and the first application was in mid-1985 in a highway in Malaysia. While the incentive to develop geotextiles may have originated from a shortage of natural fibres, now geotextiles and geogrids are produced worldwide for their cost-effectiveness in replacing natural materials and for facilitating structures that otherwise would be difficult or impossible to build.

Studies of geosynthetic barriers as “lower-cost canal liners” commenced in the USA in 1945, with the first experimental installation of a PVC-P liner in 1957 and the first installation under construction specifications in 1968. Previously hot spray-applied asphalt had been used. The first PE-HD geosynthetic barriers were manufactured and installed in Germany in the early 1970s with production increasing rapidly in the early 1980s as geosynthetic barrier lining systems became a regulated requirement in American landfills. The first prefabricated bituminous geosynthetic barrier was installed in 1974 as a barrier/separator under the ballast of a French railroad. While the incentive to develop geosynthetic barriers may have originated due to a shortage of natural clayey soils, they are now used worldwide.

Geosynthetic clay liners were introduced as an alternative, or as an assist, to natural clay in the USA in the early 1980s, with the first solid-waste landfill composite liner application being in 1986.

7.2 Empirical evidence of durability from geosynthetics extracted from the soil

7.2.1 Geotextiles

Will geotextiles last for 50 years, 100 years, or longer? To answer this question, we should start by investigating empirically what has been established over the past 45 years. Some examples giving clear evidence of durability are given below. These observations can then be compared with the results of accelerated and other laboratory tests.

In the early period, Sotton et al. (1982) reported on samples of non-woven polyester and polypropylene geotextiles retrieved from 25 sites in France, ten to fifteen years after installation. These fabrics were still functioning as filters, separators and drainage layers. Losses in tensile strength of up to 30 % were observed, but, with laboratory analysis, no chemical or biological attack could be identified. It was concluded that the reduction in strength was due mainly to mechanical damage occurring principally during installation.

In the following decade (1980-1990), Leflaive (1988) reported on a 5 m high vertical wall in Poitiers, France, which had been constructed in 1970. In this case, 5 m long polyester straps had been embedded in the concrete facing elements and anchored in the backfill, which had a pH of 8,5. Testing of the straps after 17 years showed a 2 % reduction in tensile strength within the backfill but up to 40 % reduction at the point where the straps entered the concrete facing units. Here the pH value was believed to have reached 13 to 14 at a temperature of 30 °C for some time. Subsequent analysis showed that this degradation could be explained by alkaline surface attack (25 %), internal hydrolysis (5 % to 10 %) and mechanical damage, again probably during installation.

In 1990, Wisse et al. reported on samples of 1 000 g/m^2 woven polypropylene, part of a quantity of four million square metres that had been laid as the backing of block mattresses on the sea bed of the Oosterschelde in 1978 to prevent scouring. The geotextile had been in sea water at 10 °C for nine years with a local partial pressure of 3 % oxygen. The permanent load was only 10 % of the tensile strength. The design life was expected to be determined by the time to embrittlement of the polypropylene due to oxidation. After visual examination and analysis to determine the remaining antioxidant content, the samples were subjected to accelerated oven ageing and compared with unexposed samples from the original source of material. Subsequently, the estimated time to embrittlement in sea water at 10 °C was calculated to be 80 to 120 years.

In 1994, Troost et al. reported on the condition of large quantities of woven polyester fabric retrieved from a soil-retaining structure. A multi-layered geotextile-reinforced wall, 4 m high, with slopes of 2:1 and 4:1, was constructed in the Netherlands to study possible degradation of the woven polyester fabric with time. Thirteen years later, the wall was carefully dismantled and the mechanical and chemical properties of the yarns investigated. The 50 m long embankment was oriented from east to west to provide slopes facing north and south. These slopes were partially covered with bitumen and vegetation to prevent ultraviolet attack. After the retrieved fabric had been tested, no hydrolysis could be detected on material either from the interior of the embankment or from the protected slopes, i.e. the mechanical properties, molecular weight (M_w = 33 000), and carboxyl-end-group count (23) had not changed. On the unprotected north and south slopes, reductions of 15 % to 50 % in tensile strength were observed, which were concluded to be due mainly to ultraviolet radiation and not to hydrolysis.

In 2006, Harney and Holtz investigated the degradation of a woven polyester geotextile exhumed from the embankments of the first pile-supported bridge approach in which geotextiles were used. The 100 g/m^2 multifilament woven polyester fabric was installed in 1972 in Sweden. Samples were removed in 2001 and tested together with some original archive material that had fortunately been retained. Too often, archive material is not available and aged material results are simply compared to published original material specifications. When these specifications are found to be exceeded, the material is considered “acceptable”, implying no degradation. Only when aged material parameters can be directly compared to actual measured reference (archive) material can a true picture of degradation, or lack of it, be obtained.

Although there were a few tears in the exhumed sample (possibly installation damage), microscopy of the fibre surfaces showed no obvious general degradation damage. However, there was a 50 % reduction in mean yield tensile strength, a reduction of 30 % in mean elongation at rupture, a reduction of 33 % in mean offset tensile modulus, and a 13 % reduction in mean 10 % secant modulus. But, since no installation damage measurements had previously been made, the relative amounts of installation damage and mechanical degradation could not be identified.

Harney and Holtz did note that the reduction in mean yield strength was consistent with typical reduction factors used for installation damage (1,05 to approximately 3,0) and durability (1,1 to approximately 2,0) such as presented by Elias (2000).

7.2.2 Geosynthetic barriers

While PVC-P geosynthetic barriers (geomembranes) had been used as canal liners since the mid-1950s, the widespread acceptance of geosynthetic barriers started with the use of PE-HD to construct liners in geotechnical hydraulic applications in the early 1970s. They became extensively used in landfill applications in the 1980s. During the last 10 years, many samples have been recovered, principally from landfills, to assess their functional durability. It is interesting to report a few of these findings; Hsuan et al. (1991), Dullmann et al. (1993), Brady et al. (1994), Rollin et al. (1994) and Rowe (1998).

Hsuan et al. (1991) recovered high-density polyethylene geosynthetic barrier samples from a leachate pond in service for seven years. The PE-HD geosynthetic barrier was exposed at the top sections of the pond slopes and immersed in leachate at the pond bottom. The macroscopic analysis of the recovered samples from many locations in the pond indicated no detectable changes in the geosynthetic barrier. Only minor variations in the microscopic properties were identified and no stress cracking could be measured in the collected samples.

Dullmann et al. (1993) could not observe any variation in the mechanical and chemical properties of an PE-HD geosynthetic barrier recovered from a landfill cell in operation for 8 to 10 years. Brady et al. (1994) also analysed HDPE geosynthetic barrier samples collected from many landfills. No detectable variation of their density and water adsorption could be detected. A 50 % reduction in the impact resistance for 30 year old samples and a negligible decrease for 15,5 year old samples was observed. The HDPE samples were found to be more rigid and to have a lower elongation at break.

Rollin et al. (1994) analysed PE-HD geosynthetic barrier samples recovered from top, slope, and bottom sections of a seven-year-old landfill cell. A minor increase in the yield strength and a decrease in the elongation at break were noted. The ageing of the samples collected from the cell bottom (in contact with the leachate) was slightly more advanced than for the samples collected on, and at the top of, the slopes.

Rowe (1998) recovered PE-HD geosynthetic barrier samples from a leachate pond in service for 14 years. For exposed geosynthetic barrier decreases in elongation, in the stress-cracking resistance, and in S-OIT (standard oxidation induction time) were observed. On the other hand, no S-OIT variation could be detected in samples immersed in the leachate.

These results and others are some examples giving clear evidence of durability of PE-HD geosynthetic barriers. The minor variations detected in the geosynthetic barrier properties did not affect their function during their service life.

The US Bureau of Reclamation has performed a detailed 10 year study on many different types of geosynthetic barriers installed in 34 test sections of irrigation canals in the northwest United States. A final report was issued in 2002 by Swihart and Haynes. Subgrades were described as “severe rocky”. Four generic types of liners were assessed: fluid-applied, concrete alone, exposed geosynthetic barrier, and geosynthetic barrier with concrete cover. The durabilities of these four generic types in this very challenging environment were assessed as 10 to 15, 40 to 60, 10 to 25, and 40 to 60 years, respectively. Of the geosynthetic barriers, the following observations were made after 10 years of exposure.

- PE-HD. Elongation down 90 %, OIT down 30 %, predicted service life 20 to 25 years.
- PVC-P/geotextile composite. Elongation down 70 %, predicted service life 10 to 15 years.
- CSPE. Tear strength down 60 %, predicted life 10 to 15 years.

After 10 years of exposure.

- EPDM. Elongation down 30 %, predicted service life 15 to 20 years.
- PE-LLD. Tear strength down 10 %, predicted service life 10 to 15 years.

It must be noted that subgrades were very rough, there was very little maintenance of the liners and they were continuously subject to vandalism and animal damage.

Breul (2006) reports that the bituminous liner installed directly under the ballast in the French railroad in 1974 was “still working well” in 1999.

One of the first PE-HD liners in Germany was installed in 1974 to contain jarosite sludge. A second facility was lined in 1984. Tarnowski and Baldauf (2006) reported the results of testing performed in 2005 on samples removed from both ponds. After 31 years, they found little change in the uniaxial tensile yield stress and elongation or in the break strength. However, there was a reduction of 70 % (30 % retained) in the break elongation. The single-point notched constant tensile load stress-cracking resistance (SP-NCTL) was a very low 5 h, and S-OIT on a full thickness specimen was 5 min, indicating that some of the antioxidant additive package was still present. However, to further assess S-OIT, specimens were taken from the exposed surface layer and from the centre of the geosynthetic barrier. Geosynthetic barrier thickness was not identified but was probably 2,5 mm.

After 21 and 31 years, the surface layers of the 1974 liner had S-OIT values of 71 min and 0 min, respectively, while the centre sections had values of 8,8 min and 4 min, respectively. After 21 years, the 1984 material had 5 min on the surface and 65 min in the centre. As expected, the surface layers lose their protection and oxidize first. There is some truth to the old saying that "thicker is better".

That surface layers oxidize first means that, under any applied, induced, or residual stress, stress cracks will initiate first on the surface. Once initiated on the surface, they will propagate faster through the original core material than they would have done if the surface had not been oxidized. Thus, Tarnowski and Baldauf state that the use of retained standard OIT is a more sensitive way of assessing material durability after accelerated ageing than by using tensile properties. They also state that initial OIT, retained OIT after thermo- and photo-oxidation, and stress-cracking resistance "are the [durability] properties to be well defined in every [PE-HD] geosynthetic barrier specification".

A 0,5 mm thick PVC-P geosynthetic barrier installed in an aquaculture pond in 1971 was tested by Newman et al. (2001) after samples from above and below the water level were removed in 2000. Samples were properly conditioned for laboratory testing. All properties met the NSF 54 standard first introduced in 1983. However, it was noticed that when conditioned, the samples from below the water level were somewhat stiffer than just after they had been removed, as had been observed is other similar situations. It is concluded that the chemicals that could be responsible for the extraction of plasticizer during service themselves act as plasticizer, provided the solution remains in contact with the liner. However, when the PVC-P is removed from the solution, the chemicals volatilize out of the PVC-P leaving it stiffer because of the reduced amount of original plasticizer. Therefore, it should not be assumed that a PVC-P geosynthetic barrier at the time of testing is in the same condition as it is under a liquid.

Thick PVC-P geosynthetic barriers plasticized with solid rather than liquid polymers have performed excellent exposed service for about 20 years on the upstream faces of dams high in the Alps, without any evidence of surface degradation.

Polypropylene geosynthetic barriers introduced in the early 1990s, both unreinforced (fPP) and reinforced (RPP), have had mixed performances. Some RPP test samples for exposed landfill caps have worked well for 14 years and a full-scale-exposed cap has performed well for over 9 years (Congdon et al., 1998). Other pond liners have worked well for over 15 years. However, there have been some stress-cracking problems in exposed liners, tank liners, and floating covers (Peggs, 2006) as a result of loss of additive protection. Research on this wide-ranging behaviour and on the best way to specify a durable PP geosynthetic barrier is ongoing.

7.2.3 Geogrids

Due to their relatively short times in service, geogrid performance has not been investigated to the same extent that geotextile and geosynthetic barrier performances have been evaluated. In general, Allen and Bathurst (2002) have observed that, in reinforced walls, the actual loads on the reinforcement elements are well below values required to cause creep-rupture over the design life of the structure and in some cases creep appears to have stopped completely. Thus, mechanical durability is implied to be adequate.

Good performance over an 8 to 9 year service period has been reported by Bright et al. (1994) for PE-HD geogrid soil-reinforcing elements in a concrete-faced mechanically stabilized retaining wall in Arizona, USA. In comparison with archive samples, they found "no significant change" in ultimate strength and strain, 1 000 h creep response, melt rheology, melt temperature range, crystallinity, and S-OIT.

After 10 years of service in the aggregate under railroad tracks on top of a retaining wall at the entrance to Karlsruhe's main station, Jenner and Nimmesgern (2006) found that the tensile break strength of the PE-HD geogrid still met the original material specifications but that break elongation was a little lower. Direct comparisons with archive material were planned but were not reported. Oxidative-induction-time measurements were also planned but not completed. The geogrid, the top layer of wall reinforcement, was covered by 70 cm of aggregate below one rail and 50 cm below another rail. There was some mechanical abrasion damage on the surface of the geogrid in the latter location, but not in the former. In the latter case, there were also a few cracks running along the oriented ribs (completely through the thickness of the rib) and sometimes across the transverse bars from rib to rib. In the deeper aggregate area, there were only a few surface cracks in the ribs. No distinction was made between installation damage and damage incurred during service.

Probably the most comprehensive exhumation study of geogrids was performed by Elias et al. (2000) for the US Federal Highways Administration. A total of 24 geosynthetic samples, both geogrid and high-strength geotextiles, including HDPE. PP and PET were exhumed from 12 sites after being in service for up to 20 years. A comprehensive testing programme was performed on the materials, including S-OIT on PE-HD and carboxyl-end-group count and viscosity on PET. Again, no installation damage had been previously identified so separation of installation damage and in-service mechanical damage was not possible. Elias et al. stated this is an essential component of durability studies as is full polymer characterization of the actual material, either at the time of installation or via archived and properly stored material. There appeared to be a small amount of hydrolytic degradation on the PET and no measurable OIT loss in either the PE-HD or PP, implying no microstructural degradation. They felt that such degradation would only become evident after about 30 years in service.

7.3 Summary

In general, the durability of geosynthetics is proving to be very good, but a 40 to 50 year practical history is still not very long considering that some facility owners are looking for 1 000 year or more service lifetimes for the containment of such items as low-level radioactive wastes. Nevertheless, where it has been done, the rate of mechanical degradation appears to be within quasi-theoretical calculations, using established reduction and safety factors. For potential field durability studies, it is important to define the amount of installation damage, to fully characterize the polymers and to retain properly stored archive samples. The archive samples are extremely important since, in such a young technology, tests are modified with time to focus on new parameters that may not have been used at the time of installation. For instance, consider the use of OIT to assess PP and PE-HD degradation rather than mechanical properties, and now the trend toward HP-OIT as opposed to S-OIT. Also as we are discovering, it is important to note that basic polymers, copolymers, and UV/thermal additive formulations, change with and within manufacturers, so data generated on one grade of material may not apply to another.

8 Procedure for assessment of durability

8.1 General

8.1.1 Need for testing

Many civil engineering structures are designed for long lifetimes, typically 100 years or more. Established materials, such as masonry and steel, have been used for centuries and, with appropriate maintenance, have proved durable over that time. As described in Clause 6, geosynthetics have only been in existence since the 1960s and the plastics and polymer fibres from which they are made were invented in the 1930s or later. A durability of 100 years cannot therefore be demonstrated from experience alone.

8.1.2 Testing concepts for lifetime index tests

Much is now known, however, about the manner in which plastics degrade, the rate at which this occurs, and how it can be prevented. Based on this knowledge, simple tests have been established from which a minimum durability of 25, 50 or 100 years can be predicted with reasonable certainty for the commonest geosynthetics. Examples of these tests can be found in EN 13249:2016 Annex B and EN 13493:2018 Annex A. With current knowledge, it is not possible to define a complete set of index tests for a lifetime greater than 100 years, but the laboratory testing is generally less complex but more conservative than real exposure. Prediction of durability for lifetimes >100 years has to be made on the basis of a mixture of extrapolation from experience and accelerated testing beyond basic index tests.

8.1.3 Scope of durability assessment

Clause 8 describes the procedures to be followed in the assessment of durability of geosynthetics on the basis of existing practice. It is important to consider all the chemical and physical processes that could, potentially, affect the properties of his geosynthetic over its service lifetime. The assessment relates solely to the geosynthetic and not to the soil structure in which it is used. It is not possible to predict mechanisms which depend on both soil and geosynthetic, for example clogging or frost, without detailed information on the soil and on the hydraulic properties of the site.

Satisfactory durability depends heavily on the quality of both design and installation, particularly for geosynthetic containments such as landfills and reservoirs. Most failures that have occurred to date have been due to faulty design, incorrect choice of material, and poor or uncontrolled installation practices. Reliable assurance of durability of a geosynthetic has to assume that it has been correctly installed on site. Joints and welds made on site are therefore excluded.

The procedure for assessing long-term durability is described in 8.5. Reference is made to the following subclauses:

- material (8.2.1);
- function and application (8.2.2);
- environment (8.2.3);
- mechanism of degradation (8.2.4);
- design life (8.2.5);
- “end-of-life” criterion (8.2.6).

8.2 Procedure

8.2.1 Material

The material should be defined in terms of the following, further details being given in Clause 5:

- the generic chemical nature of the polymer and other components, such as additives and coatings;
- the physical structure of the geosynthetic, e.g. thick or thin fibres forming a woven or non-woven fabric, extruded grid, coated fibrous strip, geosynthetic clay barrier, continuous sheet;
- junctions forming part of the structure of the geosynthetic.

8.2.2 Function and application

The functions of the geosynthetic should be defined, as described in ISO 10318-1, as barrier function, drainage, filtration, protection, reinforcement, separation and surface erosion control. Not all these functions require a lifetime of 100 years. Some applications, such as construction roadways (separation) or prevention of slip failure during settlement (reinforcement), are temporary by design; in others, it may be easy to repair or replace the geosynthetic. Soil reinforcement, drainage and barriers for landfill and tunnels, however, are typical examples of where a long lifetime is required and repair or replacement are possible only at great expense.

8.2.3 Environment

The environment should be defined as in 6.1 (above ground) and 6.2 (below ground), including the design temperature for the application in hand. In the absence of a specific design temperature, 20 °C should be used as the default value for applications below ground, noting the comments on extreme situations given in 6.2.

8.2.4 Mechanism of degradation

Each aspect of the environment, and its potential degrading effect, should be considered for each application, as defined in 8.2.2, and placed in order of significance. Some aspects may be considered as not significant. Others may be significant only when considered in combination (e.g. pH and temperature). Types of degradation that should be considered include the following (for guidance see 6.3 and 6.4):

- mechanical damage due to coarse soils, leading to a reduction in strength, or to perforations;
- oxidation (e.g. of PP and PE), leading to a reduction in strength or surface cracking, retarded by the inclusion of antioxidant stabilizers;
- photo-oxidation due to ultraviolet light, general weathering;
- hydrolysis (e.g. of PET and PA) in aqueous solutions, leading to a reduction in strength;
- alkaline attack (e.g. on PET and on additives in PP and PE), leading to a reduction in cross-section and strength;
- acid attack (e.g. on PA and on additives in PP and PE) under aerobic conditions, leading to a reduction in strength;
- the effect of solvents, which may swell polymers, leach out additives or cause environmental stress cracking under load;
- the effects of waste effluents and leachates;
- compressive or tensile creep;
- freeze-thawing, wet-dry cycles and ion exchange (principally of GBR-C).

8.2.5 Design life

The design life should be defined as described in 4.3.

8.2.6 The “end-of-life” criterion

The end of life should be defined. This is the point when the geosynthetic can no longer function satisfactorily. It should be related to the application and function and, where possible, defined quantitatively (see 4.5). Examples of end-of-life criteria are

- percentage reduction in strength and/or elongation (e.g. 30 %),
- percentage reduction in drainage cross-section (e.g. 50 %),
- observed rupture,
- increase in permeability (e.g. 25 %),
- residual antioxidant stabilizers in PP or PE (e.g. 10 %), preceding mechanical degradation and
- residual OIT or HP-OIT.

8.3 Degradation during storage and installation

8.3.1 Weathering

The effect of weathering should be defined. Many geosynthetics are exposed to light during storage and on the construction site but are covered in service. Degradation during exposure to light is due to the ultraviolet component of solar radiation, whether direct sunlight or diffuse light, aided by heat and moisture. Some weathering effects are due to the alternation of day and night or of wet and dry periods.

It is therefore recommended that all geosynthetics should be tested for their resistance to weathering, using an accelerated test which provides a high level of radiation coupled with cycles of temperature and moisture, such as ASTM D4355 and EN 12224.

According to hEN 13493-18 and hEN13249-16, the EN 12224 standard method is based on the 50 MJ/m^2 radiant exposure (quantity of incident ultraviolet radiation), corresponding to one month's exposure in Southern Europe in summer. The strength retained by a geotextile at the end of the test, together with the specific application of the product, will define the length of time during which the material may be exposed on site, as shown in Table 4:

Table 4 — Installation exposure period for geotextiles

Application	Retained strength after testing according to EN 12224	Maximum exposure time (uncovered) during installation
Reinforcement or applications where long-term strength is a significant parameter	>80 %	1 month[a]
	60 % to 80 %	2 weeks
	<60 %	cover on day of installation
Other applications	>60 %	1 to 4 months[a]
	20 % to 60 %	2 weeks
	<20 %	cover on day of installation

[a] Exposure of up to four months may be acceptable, depending on the season and location.

In the case of geosynthetic barriers, no testing is considered necessary if the exposure time on site is less than three days and the barrier remains shielded from light throughout its lifetime.

According to hEN 13493-18, if the exposure time is to be up to 1 year, then the material should retain 75 % of its initial strength and elongation after a radiant exposure of 350 MJ/m^2.

Extended artificial weathering tests using methods similar to those in EN 12224 are required for materials which are to be exposed for longer durations. If the radiation is increased too much, the temperature of the geosynthetic rises to a point where the accelerated test is no longer representative of the performance in service. This limits the degree of acceleration to about a factor of three, with the result that many years' testing may be required to simulate the service life of a geosynthetic exposed permanently to light.

8.3.2 Mechanical damage

For geotextiles, the effect of damage during installation should be determined (see 6.4.4). For geosynthetic barriers damage during installation is limited by strict control of the materials in contact supported by a geophysical survey of the complete installation. In the case of poor installation procedures, defects will be introduced which are likely to lead to premature failure.

8.4 Short-, medium-, and long-term applications

For applications where the geosynthetic has a design life of less than five years in natural soils and the consequences of failure are low, only tests for weathering and, if relevant, mechanical damage are necessary. In some such applications, the soil structure itself may have a longer design life, but the geosynthetic no longer plays an essential part. For such duration, the geosynthetic is used for non-reinforcing applications, in natural soils with pH between 4 and 9 and with soil temperature less than 25 °C. The geosynthetic does not contain biodegradable materials, but may contain PCM or PIM in its formulation.

For applications with design lives up to 100 years in natural soils, with pH values between 4 and 9, and at temperatures less than 25 °C and for some geosynthetics, durability can be assured on the basis of screening tests. These index tests, ISO 13438, EN 14030, EN 12447, ASTM D5819, ASTM D6213, ASTM D6388 and ASTM D6389, are designed to exclude materials where there is any doubt concerning their durability. Table 3 lists corresponding tests for geosynthetic barriers. These are based on the methods of accelerated testing and are obtained from current knowledge on the polymer degradation process and rate. They may be used for minimum life prediction as the conditions in the tests are generally extreme, necessitated by the short duration required, and considered as conservative. As an example, for EN 12447, which covers the hydrolysis of polyester fibre products, there is sufficient confidence to state a minimum strength retention after 25, 50 and 100 years on the basis of the index test, implying an activation energy of 105 kJ/mol. Not all the mentioned standards give the same lifetime as a result, details are therefore to be checked by these standards.

Screening tests are not intended to be regular quality-control tests, and are used as an indicative evaluation of the minimum service duration (which is different from time to failure) of the tested geosynthetic.

8.5 Assessment of long-term durability

8.5.1 General

For all situations other than those described in 8.3 and 8.4, make an assessment of long-term durability. Such situations include

- all applications with design lifetimes exceeding 50 years,
- all applications of geosynthetics susceptible to hydrolysis in which highly alkaline environments are present with pH >10,0, particularly in the presence of lime, cement or concrete, or for long design lives with pH >9,
- applications of polyamide in aerobic acid environments, landfill sites or contaminated ground,
- applications in which the geosynthetic is likely to be exposed to temperatures greater than 25 °C or less than 0 °C for a significant period,
- recycled materials, for which manufacturers are expected to maintain sufficient control over the uniformity of their feedstock.

Consider all those items listed in 8.2.4 and in addition:

- past experience, noting the conditions of that experience;
- results of tests, whether index or performance tests: in performance tests the general method for testing and evaluation is defined; certain parameters are site-specific, such as the choice of backfill or landfill leachate;
- sites on which the geosynthetic is currently being monitored;
- the confidence in the data and the relation between the duration of testing and the design life.

8.5.2 Evidence from service

Consider any relevant evidence from geosynthetics which have been in service.

Measurements of the degradation in real service environments are the most authoritative evidence for durability. Since geosynthetics have only been used since the 1960s, however, the evidence for long-term durability is limited and frequently incomplete, or relates to conditions that differ from those for which the assessment is being made. Some examples are given in Clause 7. Where such information is available, the following should be noted.

- As much information as possible should be obtained on the material itself, as described in Clause 5. If possible, archive material produced at the same time should be made available for comparison. Unfortunately, the value of data from archive material can be limited because the storage conditions have not been controlled or defined sufficiently. Thus, the importance of well-defined analytical data increases.

- The environment should be defined in as much detail as possible, as described in 6.1 and 6.2.
- The duration over which the material was in service.
- All observed changes.

The effects of mechanical damage and of exposure to light during installation, whether correctly or incorrectly performed, should be identified so that they can be separated from long-term degradation. It may be possible to find areas of material which have not been damaged or exposed to light for comparison.

The rate of change should be determined, noting that it may vary with time. It should relate to the mechanism degradation believed to be dominant for the geosynthetic, and should be statistically significant. Statements that nothing has changed serve only to help provide an assurance of durability for comparable lifetimes. The environmental conditions experienced in the past should be related to the future design conditions, which are frequently more severe than those actually experienced. When accelerated tests have been performed, it may be possible to use the parameters of Arrhenius' formula to convert from one temperature to another.

Frequently, the material used in the past will differ from that for which an assessment is to be made in the future. Products change with time and it will be necessary to make a subjective judgement on the level of similarity.

Failures at joints should not be taken as typical of the bulk material while, if joint failure is the end of life, then the prediction should be based on this alone.

The rate of change, adjusted to future design conditions, should be extrapolated to the service life to establish whether the "end-of-life" criterion will have been reached. Extrapolation should use a formula based on the degradation mechanism if one is available. If not, the simplest formula that fits the measurements should be used (Occam's principle). Power law relations are recommended; polynomials are not. Computer-assisted fits and predictions should be regarded with caution unless the basis for the calculation and its limitations are understood. Particular care should be taken in using logarithmic scales which condense long periods of real future time into conveniently short distances on a diagram. Current practice is to extrapolate by durations of up to ten times without penalty; extrapolation by larger amounts should incur a precautionary factor unless supported by other data — see, for example, ISO 20432:2007, Clause 10. The user should never forget how long a hundred years really is. Ultimately, he is the judge of what is acceptable.

8.5.3 Accelerated testing

8.5.3.1 General

Perform appropriate accelerated tests.

In accelerated testing, the rate of degradation is increased by increasing the frequency of the degrading agent, by increasing the severity of the agent causing degradation, or most commonly by changing the temperature. For stabilized materials, further acceleration is possible by intensifying the leaching process (e.g. evaporation, extraction, migration). Most of accelerated tests are already known and widely defined in scientific literature for thermoplastics. However, it may be more difficult to find accelerated tests for elastomeric materials which are subjected to degradation in specific conditions.

8.5.3.2 Increasing frequency

Increasing the frequency of the degrading agent is only possible when the agent is intermittent. The method is widely used in industry, for example automobile design. For geosynthetics, this method is only relevant in cases such as traffic loading and tidal surges, where the duration under actual load can be condensed into a period short enough for testing to be performed under conditions that are otherwise equivalent to those anticipated in service.

8.5.3.3 Increasing severity

Increasing the severity of the agent of degradation includes methods such as raising the chemical concentration, the availability of oxygen, the intensity of UV radiation (see 8.3.1) or the mechanical load. If the relation between the rate of degradation and the severity (or concentration) is known, then it may be possible to define a single test. If not, multiple tests should be performed in order to determine both the rate of degradation and its dependence on the intensity of the agent. In creep-rupture, for example, a range of high loads is applied to different specimens and the times to rupture monitored. A graph of load against time, or more commonly the logarithm of time, defines the time to rupture (the inverse of the rate of degradation) and how this time depends on load. The graph can then be extrapolated from the short lifetimes and high loads used in testing for the long lifetimes and lower loads applied in service, with the object of defining a design load corresponding to the service lifetime. For further details, see ISO/TR 20432.

8.5.3.4 Increasing temperature

Temperature is very widely used to accelerate both chemical and physical processes. Prediction of long-term degradation from accelerated tests is only valid if the mechanisms of degradation and failure are the same at all the test temperatures and the service temperature.

Extrapolation makes use of the Arrhenius formula,

$$A = A_0 \exp[-E/(R \cdot T)]$$

where

A is the rate of degradation;

A_0 is a constant;

E is the activation energy of the process, in J/mol;

R is the universal gas constant (8,314 J/mol·K);

T is the absolute temperature, in K (temperature in °C + 273,15).

Tests are set up at different temperatures and the rate of degradation, A, measured in each case. This “rate” may, for example, be a rate of diffusion, the inverse of the time to failure or the inverse of the time to halve the strength. The natural logarithm of the rate of degradation ($\ln A$) is then plotted against the inverse of the absolute temperature ($1/T$). If the points lie on a straight line, the line can be extrapolated to derive the rate of degradation at the service temperature. The gradient of the line is $-E/R$.

In planning Arrhenius tests, the maximum temperature is likely to be limited by a transition such as the melting point and the minimum temperature by the predicted duration of the test. Temperature steps should be no greater than 10 °C. When measurements are to be made at set time intervals, these should be spaced logarithmically. Reserve specimens should be installed in case the durations have to be extended. Planning Arrhenius tests is simpler if the answer can be estimated in advance.

Arrhenius tests are used for the determination of screening tests taking into account a wide range of products in the same family, considering the most conservative case for a given service duration [e.g. EN 13249 (Annex B) and EN 13493 (Annex A)].

It is generally recommended that the lowest test temperature should be not more that 20 °C above the design temperature, and that extrapolation over time should be by no more than a factor of ten. If this is not possible, generally because the duration of testing would be too long, then a safety factor should be applied to the predicted available property.