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REPORT

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Guidelines for the determination of the long-term strength of geosynthetics for soil reinforcement

Lignes directrices pour la détermination de la résistance à long terme des géosynthétiques pour le renforcement du sol

Reference number
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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ISO/TR 20432 was prepared by Technical Committee ISO/TC 221, *Geosynthetics*.

Guidelines for the determination of the long-term strength of geosynthetics for soil reinforcement

1 Scope

This Technical Report provides guidelines for the determination of the long-term strength of geosynthetics for soil reinforcement.

This Technical Report describes a method of deriving reduction factors for geosynthetic soil-reinforcement materials to account for creep and creep rupture, installation damage and weathering, and chemical and biological degradation. It is intended to provide a link between the test data and the codes for construction with reinforced soil.

The geosynthetics covered in this Technical Report include those whose primary purpose is reinforcement, such as geogrids, woven geotextiles and strips, where the reinforcing component is made from polyester (polyethylene terephthalate), polypropylene, high density polyethylene, polyvinyl alcohol, aramids and polyamides 6 and 6,6. This Technical Report does not cover the strength of joints or welds between geosynthetics, nor whether these might be more or less durable than the basic material. Nor does it apply to geomembranes, for example, in landfills. It does not cover the effects of dynamic loading. It does not consider any change in mechanical properties due to soil temperatures below 0 °C, nor the effect of frozen soil. The Technical Report does not cover uncertainty in the design of the reinforced soil structure, nor the human or economic consequences of failure.

Any prediction is not a complete assurance of durability.

2 Normative references

The following referenced documents are indispensable for the application 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, *Geosynthetics — Terms and definitions*

3 Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

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

3.1.1
long-term strength
load which, if applied continuously to the geosynthetic during the service lifetime, is predicted to lead to rupture at the end of that lifetime

3.1.2
long-term strain
total strain predicted in the geosynthetic during the service lifetime as a result of the applied load

3.1.3

reduction factor

factor (⩾ 1) by which the tensile strength is divided to take into account particular service conditions in order to derive the long-term strength

NOTE In Europe, the term 'partial factor' is used.

3.1.4

characteristic strength

95 % (two-sided) lower confidence limit for the tensile strength of the geosynthetic, approximately equal to the mean strength less two standard deviations

NOTE This should be assured by the manufacturer’s own quality assurance scheme or by independent assessment.

3.1.5

block shifting

procedure by which a set of data relating applied load to the logarithm of time to rupture, all measured at a single temperature, are shifted along the log time axis by a single factor to coincide with a second set measured at a second temperature

3.1.6

product line

series of products manufactured using the same polymer, in which the polymer for all products in the line comes from the same source, the manufacturing process is the same for all products in the line, and the only difference is in the product mass per area or number of fibres contained in each reinforcement element

3.2 Abbreviated terms

CEG	carboxyl end group
DSC	differential scanning calorimetry
HALS	hindered amine light stabilizers
HDPE	high density polyethylene
HPOIT	high pressure oxidation induction time
LCL	lower confidence limit
MARV	minimum average roll value
OIT	oxidation induction time
PA	polyamide
PET	polyethylene terephthalate
PP	polypropylene
PTFE	polytetrafluorethylene
PVA	polyvinyl alcohol
RF_{CH}	reduction factor to allow for chemical and biological effects
RF_{CR}	reduction factor to allow for the effect of sustained static load
RF_{ID}	reduction factor to allow for the effect of mechanical damage
RF_{W}	reduction factor to allow for weathering
SIM	stepped isothermal method
TTS	time-temperature shifting

3.3 Symbols

A_i	time-temperature shift factor
b_a	gradient of Arrhenius graph
d_{50}	mean granular size of fill
d_{90}	granular size of fill for 90 % pass (10 % retention)
f_s	factor of safety
G, H	parameters used in the validation of temperature shift linearity (see 7.4)
m	gradient of line fitted to creep rupture points (log time against load); inverse of gradient of conventional plot of load against log time.
M_n	number averaged molecular weight
n	number of creep rupture or Arrhenius points
P	applied load
R_1	ratio representing the uncertainty due to extrapolation
R_2	ratio representing the uncertainty in strength derived from Arrhenius testing
S_sq	sum of squares of difference of log (time to rupture) and straight line fit
S_xx, S_xy, S_yy	sums of squares as defined in derivation of regression lines in 9.4.3
σ_0	standard deviation used in calculation of LCL
t	time, expressed in hours
t_{90}	time to 90 % retained strength
t_D	design life
t_deg	degradation time during oxidation
t_ind	induction time during oxidation
t_LCL	LCL of time to a defined retained strength at the service temperature
t_max	longest observed time to creep rupture, expressed in hours
t_{n-2}	Student's t for $n - 2$ degrees of freedom and a stated probability
t_R	time to rupture, expressed in hours
t_s	time to a defined retained strength at the service temperature
T	load per width
T_B	batch tensile strength (per width)
T_char	characteristic strength (per width) (see 6.1)
T_x	unfactored long-term strength (see 9.4.3)

T_{D}	long-term strength per width (including factor of safety)
T_{DR}	residual strength
θ_{j}	temperature of accelerated creep test
θ_{K}	temperature
T_{LCL}	LCL of T_{char} due to chemical degradation
θ_{s}	service temperature
x	abscissa: on a creep rupture graph the logarithm of time, in hours
$\bar{x}$	mean value of x
x_{i}	abscissa of an individual creep rupture point
x_{p}	predicted time to rupture
y	ordinate: on a creep rupture graph, applied load expressed as a percentage of tensile strength, or a function of applied load
y_0	value of y at 1 h (log $t = 0$)
$\bar{y}$	mean value of y
y_{i}	ordinate of an individual creep rupture point
y_0	value of y at time 0, derived from the line fitted to creep rupture points

4 Design procedure

4.1 Introduction

The design of reinforced soil structures generally requires consideration of the following two issues:

a) the maximum strain in the reinforcement during the design lifetime;

b) the minimum strength of the reinforcement that could lead to rupture during the design lifetime.

In civil engineering design, these two issues are referred to as the serviceability and ultimate limit state respectively. Both factors depend on time and can be degraded by the environment to which the reinforcement is exposed.

4.2 Design lifetime

A design lifetime, t_{D}, is defined for the reinforced soil structure. For civil engineering structures this is typically 50 to 100 years. These durations are too long for direct measurements to be made in advance of construction. Reduction factors have therefore to be determined by extrapolation of short-term data aided, where necessary, by tests at elevated temperatures to accelerate the processes of creep or degradation.

4.3 Causes of degradation

Strain and strength may be changed due to the effects of the following:

- mechanical damage caused during installation;
- sustained static (or dynamic) load;
- elevated temperature;
- weathering while the material is exposed to light;
- chemical effects of natural or contaminated soil.

4.4 Design temperature

The design temperature should have been defined for the application in hand. In the absence of a defined temperature or of site specific in-soil temperature data, the design temperature should be taken as the temperature which is halfway between the average yearly air temperature and the normal daily air temperature for the hottest month at the site. If this information is not available, 20 °C should be used as the default value.

Many geosynthetic tests are performed at a standard temperature of (20 ± 2) °C. If the design temperature differs, appropriate adjustments should be made to the measured properties.

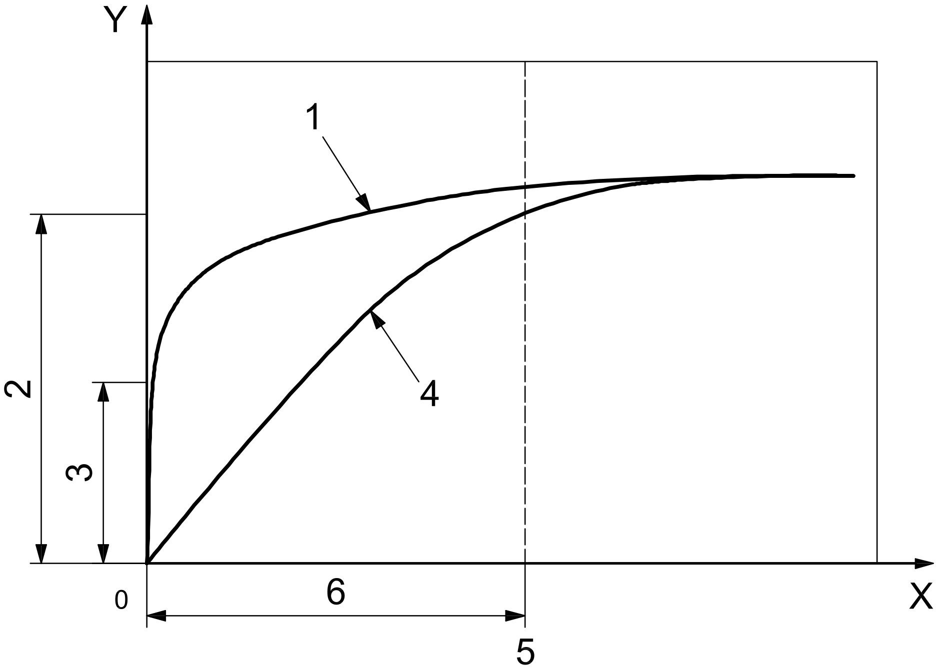
This Technical Report does not cover the effects of temperatures below 0 °C (see Clause 1).

5 Determination of long-term (creep) strain

5.1 Introduction

The design specification may set a limit on the total strain over the lifetime of the geosynthetic, or on the strain generated between the end of construction and the service lifetime. In the second case, the time at “end of construction” should be defined, as shown in Figure 1. When plotted against log t, even a one-year construction period should have negligible influence on the creep strain curve beyond 10 years.

Levels of creep strain encountered in the primary creep regime (creep rate decreasing with time) are thought not to adversely affect strength properties of geosynthetic reinforcement materials.



Key

1	Laboratory creep test	5	New time = 0 for post construction creep
2	Load ramp period on wall	6	Wall construction time
3	Load ramp period in creep test	X	Time
4	Loading and creep of reinforcement in wall	Y	Strain

Figure 1 — Conceptual illustration for comparing the creep measured in walls to laboratory creep data

5.2 Extrapolation

Creep strain should be measured according to ISO 13431 and plotted as strain against the log t. It may then be extrapolated to the design lifetime. Extrapolation may be by graphical or curve-fitting procedures, in which the formulae applied should be as simple as is necessary to provide a reasonable fit to the data, for example, power laws. The use of polynomial functions is discouraged since they can lead to unrealistic values when extrapolated.

5.3 Time-temperature superposition methods

Time-temperature superposition methods may be used to assist with extending the creep curves. Creep curves are measured under the same load at different temperatures, with intervals generally not exceeding 10 °C, and plotted on the same diagram as strain against log t. The lowest temperature is taken as the reference temperature. The creep curves at the higher temperatures are then shifted along the time axis until they form one continuous “master” curve, i.e. the predicted long-term creep curve for the reference temperature. The shift factors, i.e. the amounts (in units equivalent to log t) by which each curve is shifted, should be plotted against temperature where they should form a straight line or smooth curve. The cautions given in 7.6 should be noted.

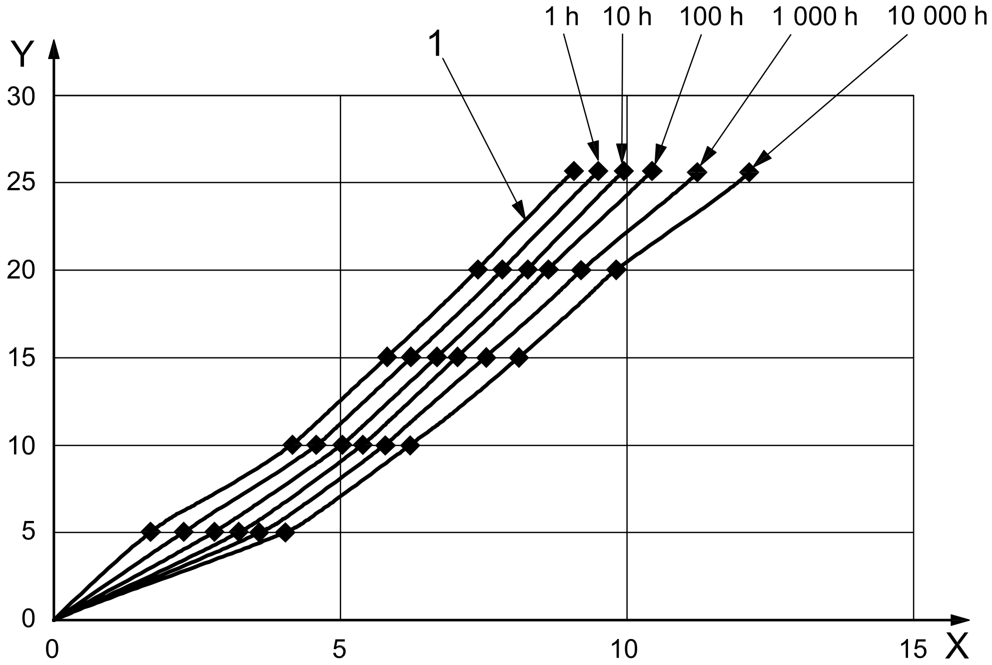
Experience has shown the strains on loading are variable. Since the increase in strain with time is small, this variability can lead to wide variability in time-temperature shifting (TTS). The stepped isothermal method (SIM) described in 7.5 avoids this problem by using a single specimen, increasing the temperature in steps, and then shifting the sections of creep curve measured at the various temperatures to form one continuous master curve.

If a more accurate measure of initial strain is required, five replicates are recommended at each load. Some of these can be of short duration, e.g. 1 000 s. At a series of loads, fewer replicates at each load will suffice if the data are pooled using regression techniques. One approach is to use regression analysis to develop an isochronous load versus strain curve at 0,1 h. The creep curve should then be shifted vertically to pass through the mean strain measured after 0,1 h.

If the lowest test temperature is below the design temperature, the shift factor corresponding to the design temperature should be read off the plot of shift factor against temperature. The time-scale of the master curve should then be adjusted by this factor.

5.4 Isochronous curves

From the creep curve corresponding to each load, read off the strains for specified durations, typically 1 h, 10 h, 100 h, etc., and including the design lifetime. Set up a diagram of load against strain. For each duration, plot the points of load against strain for the corresponding durations (see Figure 2). These are called isochronous curves. Where a maximum strain is permitted over the design lifetime, or between the end of construction (e.g. 100 h) and the design lifetime, it is possible to read off the corresponding loads from these curves. Where the strain is measured from zero, note that in geosynthetics strains are measured from a set preload (defined in ISO 10319 and ISO 13431 as 1 % of the tensile strength) and that some woven and particularly non-woven materials may exhibit considerable irreversible strains below this initial loading. See [2] in the Bibliography for additional details on creep strain characterization.



Key

X Strain

Y Load

Figure 2 — Isochronous diagram

5.5 Weathering, chemical and biological effects

Creep strain is generally insensitive to limited weathering, chemical and biological effects. In addition, creep strains are in general not affected by installation damage, unless the damage is severe, or unless the load level applied is very near the creep limit of the undamaged material. In most cases, the load level applied is well below the creep limit of the material. See [3] in the Bibliography for additional details on this issue. Thus, no further adjustment is generally required beyond the effect of temperature.

Note, however, that artificially contaminated soils may contain chemicals, such as organic fuels and solvents, which can affect the creep of geosynthetics. If necessary, perform a short-term creep test according to ISO 13431 on a sample of geosynthetic that is immersed in the chemical or has just been removed from it. If the creep strain is significantly different, do not use this geosynthetic in this soil.

6 Determination of long-term strength

6.1 Tensile strength

The characteristic strength, T_{char}, is taken as the basis for the long-term strength. T_{char} is typically a statistical value generated from the mean strength of production material less two standard deviations sometimes referred to as the minimum average roll value (MARV), unless otherwise defined.

6.2 Reduction factors

T_{char} can then be divided by the following four reduction factors, each of which represents a loss of strength determined in accordance with this Technical Report, to arrive at the long-term strength T_{D}:

- RF_{CR} is a reduction factor to allow for the effect of sustained static load at the service temperature;

NOTE The effect of dynamic loads is not included.

- RF_{ID} is a reduction factor to allow for the effect of mechanical damage;
- RF_{W} is a reduction factor to allow for weathering during exposure prior to installation or of permanently exposed material;
- RF_{CH} is a reduction factor to allow for reductions in strength due to chemical and biological effects at the design temperature (see 4.4).

In addition to the reduction factors, a factor of safety, f_{s}, takes into account the statistical variation in the reduction factors calculated (see 6.1). It does not consider the uncertainties related to the soil structure and the calculation of loads.

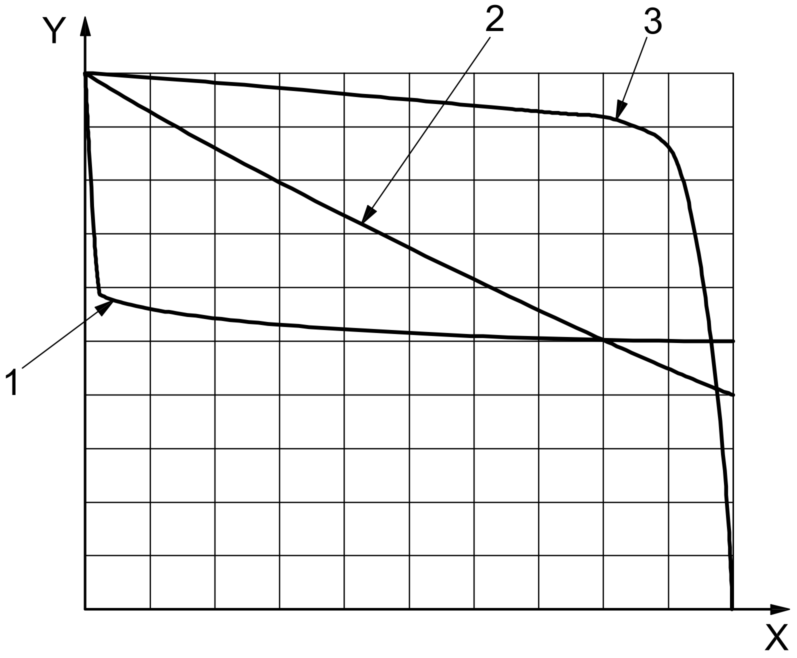
6.3 Modes of degradation

Degradation of strength can be divided into three Modes according to the manner in which they take place with time:

- Mode 1: Immediate reduction in strength, insignificant further reduction with time;
- Mode 2: Gradual, though not necessarily constant, reduction in strength;
- Mode 3: No reduction in strength for a long period; after a certain period, onset of rapid degradation.

For Mode 1, of which installation damage is an example, it is appropriate to reduce the tensile strength by an appropriate time-independent reduction factor. For Mode 2, where there is a progressive reduction in strength, the tensile strength will be reduced by a time-dependent reduction factor. For Mode 3, it is not appropriate to apply a reduction factor to the tensile strength but rather to restrict the service lifetime.

These Modes are depicted schematically in Figure 3.



Key

1 Mode 1
2 Mode 2
3 Mode 3
X Time
Y Retained strength

Figure 3 — Retained strength plotted against time for the three Modes of degradation

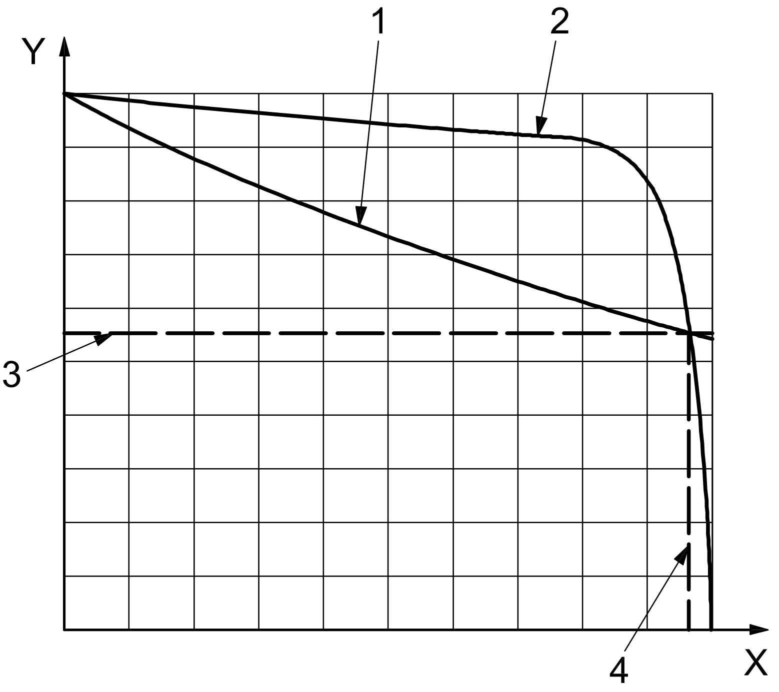
7 Creep rupture

7.1 Introduction

Creep rupture, or lifetime under sustained load, is determined by measuring times to rupture of up to at least 10 000 h. The results are extrapolated to predict longer lifetimes at lower loads and thereby the reduction factor RF_{CR}.

This procedure may be supported by measurements at higher temperatures. Conventional TTS of results obtained on multiple specimens at elevated temperatures provides an improved prediction of the long-term behaviour at ambient temperature. In the SIM, the temperature of a single specimen is increased in steps. The sections of creep strain curve measured at each temperature step are then combined to predict the long-term creep strain and rupture lifetime.

It should be noted that a creep rupture diagram depicts applied load plotted against time to rupture and is not a statement of the loss of strength under continuous load. It has been predicted on the basis of accelerated tests that many geosynthetics exposed to sustained load do not in fact significantly diminish in strength until close to the end of their predicted life. When the strength equals the applied load, the material ruptures (see Figure 4). Sustained load is therefore a Mode 3 form of degradation.



Key

1 Creep rupture
2 Residual strength
3 Applied load
4 Lifetime
X Time
Y Applied load, residual strength

Figure 4 — Creep rupture and residual strength as a function of time

The creep rupture curve shows the predicted lifetime corresponding to a particular applied load. During that lifetime, the strength of the geosynthetic follows the residual strength curve, falling to equal the applied load at the moment of rupture.

7.2 Measurement of creep rupture: conventional method

For limit state design, the creep rupture behaviour of the product should be measured according to ISO 13431 with a minimum of 12 measurements. As a guide, at least four of the test results should have rupture times between 100 h and 1 000 h, and at least four of the test results should have rupture times of 1 000 h to 10 000 h, with at least one additional test result having a rupture time of approximately 10 000 h (1,14 years) or more.

Specimens should be tested in the direction in which the load will be applied in use. The tensile strength of the same batch, T_B, of the material in the same direction should be determined according to ISO 10319 using grips similar to those used for creep rupture testing. Loads applied during the creep rupture tests should be expressed as a percentage of T_B. The nature of the failure should be observed and recorded.

It is recommended that creep strain is measured as well as time to rupture, since this can assist with conventional time-temperature strain shifting and in identifying any change in behaviour that could invalidate extrapolation of the results. This practice will also permit laboratory creep data collected at moderate differences (plus or minus 10 °C) in test temperature to be corrected to the desired reference temperature. Similar moderate changes in reference temperature will be facilitated under this practice as well.

The temperature should be as stated in ISO 13431 and ISO 10319; if a different temperature, for example, the design temperature, is used then it should be the same for both tensile and creep rupture measurements. Further tests at elevated temperature may be used for the purposes of TTS.

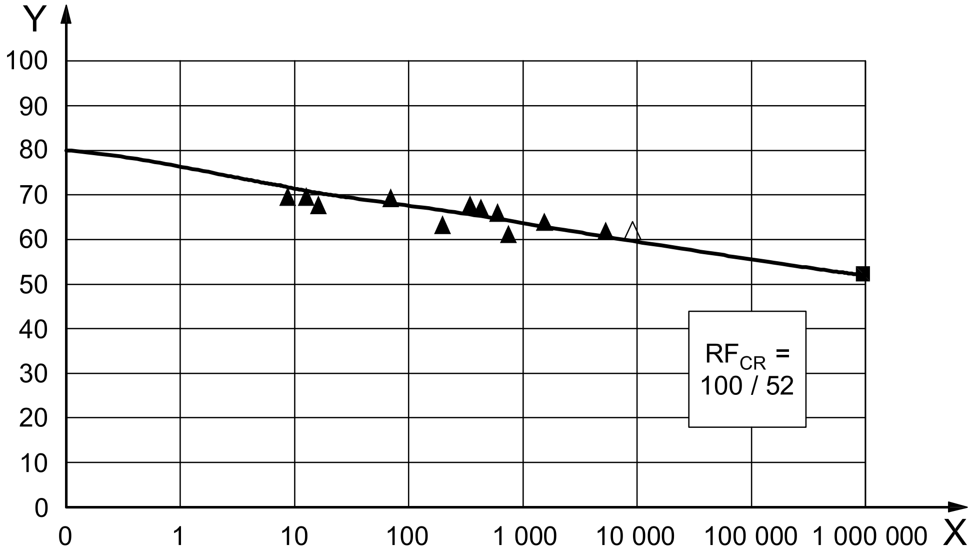
The creep rupture data for the product should be tabulated as:

- load per width T, as percentage of the batch tensile strength, T_B;
- time to rupture, t_R, in h;
- log t to rupture;
- observations on the failure, including the strain at failure or the strain at the point where the rate of creep starts to increase (tertiary creep) and, where visible, the nature of the fracture surface, e.g. ductile, semi-brittle or brittle and smooth;
- creep strain data, if available, particularly if conventional time-temperature strain shifting is applied;
- whether the test was conventional (20 °C), time-temperature accelerated, SIM or was performed on a similar material as supporting data.

Incomplete tests may be included, with the test duration replacing the time to rupture, but should be listed as such. The procedure for handling incomplete tests is described in 7.3.

7.3 Curve fitting (conventional method)

The data, including any relevant supporting data, should be plotted as $y = T$ (expressed as a percentage of T_B) against $x = \log t_R$, which should yield a linear plot (see Figure 5). This is referred to as a semi-logarithmic plot and has been shown to apply to polyester reinforcements. If the plot is not linear, it may be necessary to plot the ordinate (y) as a function of applied load to achieve a linear plot. The use of the function $y = \log T$, resulting in a double logarithmic plot, has been shown to apply to polyethylene and polypropylene reinforcements. Where a function of T is used, it should preferably be based on a known physical model.



Key

X Time (h)

Y Load per width T, as % tensile strength

Figure 5 — Creep rupture diagram with straight line fit

Fit a straight line using statistical regression analysis. In the following, x equals log t_R and y equals T or a function of P. The creep rupture points, total number n, are denoted as (x_i, y_i). Note that in contrast to most scientific plots, the independent variable is plotted on the y axis and the dependent variable is plotted on the x axis. The formulae that follow therefore differ from those conventionally found by having x and y interchanged.

The straight line fit (regression line) is given by the formula:

$$x = \bar{x} + m(y - \bar{y})$$

where

$$\bar{x} = \frac{\sum x_i}{n} \quad \text{and} \quad \bar{y} = \frac{\sum y_i}{n}$$

summed over all points (x_i, y_i).

m is given by the formula:

$$m = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sum (y_i - \bar{y})^2}$$

Because of the interchange of x and y, the gradient of the graph is equal to $1/m$. For a semi-logarithmic diagram, this should be expressed as percentage tensile strength per decade of time. The gradient should be a negative value.

The intercept y_0 on the line $x = 0$ (i.e. at log $t = 0$; $t = 1$ h) is given by:

$$y_0 = \bar{y} - \bar{x} / m$$

The accepted practice for incomplete tests is as follows. The regression should first be performed with the incomplete tests excluded. The time to failure for an incomplete test should then be determined for the corresponding value of T. If the predicted time to failure is less than the duration of the incomplete test, the point may be added and the regression recalculated. If the predicted time to failure is greater than the duration of the incomplete test, the point should continue to be excluded. In Figure 5 the incomplete test shown by an open triangle is included since it lies to the right of the regression line.

Extend the regression line to the design lifetime, for example in Figure 5 where for a design lifetime of 1 000 000 h, T = 52 % of tensile strength. RF_{CR} = 1/52% = 100/52 = 1,92

Record the duration of the longest test that has ended in rupture, or the duration of the longest incomplete test whose duration has been included in the regression calculation: this duration is denoted as t_{max}.

7.4 Curve fitting for time-temperature block shifting of rupture curves

If data obtained at higher temperatures θ_i are to be included for the purposes of acceleration, tabulate the values of y_i and t_R as in 7.3 together with the temperatures θ_j. For each temperature θ_i, assign a nominal shift factor A_j. Assign nominal values to the constants y_0 and m. Include the test points derived at 20 °C for which $A_i = 0$. Then proceed as follows.

For each measured value of t_R, calculate the shifted log time $x_i = \log t_R + A_j$.

For each value of y_i, calculate the logarithm of the predicted time to rupture $x_p = (y_i - y_0)m$.

For each pair of values, calculate the square of the difference $(x_i - x_p)^2$.

Derive the sum of squares $S_{sq} = \Sigma_i (x_i - x_p)^2$.

Using a spreadsheet optimization programme, minimize S_{sq} as a function of all A_j, y_0 and m.

Plot y_i against x_i and add the straight line fit as in 7.3.

Plot A_i against θ_i. Check that the line passes through the point (20 °C, 0) and is then straight or lightly curved, such that if the curve is approximated by the quadratic equation

$$A_j = G(\theta_i - 20) + H(\theta_i - 20)^2$$

then $-0{,}003 < G/H < 0{,}003$. If not, the validity of the tests should be reviewed.

For example in Figure 6, the regression creep rupture lines for 20 °C, 40 °C and 60 °C are assumed to be parallel. The 40 °C and 60 °C lines and associated points have been shifted to the right until they coincide with the 20 °C line to which they form an extension. Temperature steps $\leqslant$ 10 °C are recommended for PE and PP.

This procedure assumes that the creep rupture curves at all temperatures are linear and parallel, which has been found empirically to apply to polyester (semi-log plots) and polypropylene (log/log plots). It should be pointed out that the theory of Zhurkov [4] in the Bibliography, which assumes that the fracture process is activated thermally with the additional effect of applied stress, predicts that the creep rupture characteristics should be straight when plotted on a semi-logarithmic diagram, and that their gradients should be stress-dependent. This theory has not provided a better fit to experimental creep rupture data than the empirical method used here, but experience has shown that the shift factors can be stress-dependent and block shifting ignores this.

7.5 Strain shifting and the stepped isothermal method

Long-term rupture data can be obtained through the use of the classical TTS of creep strain data. Strain shifting as described in 5.2 can be applied to creep curves terminated in rupture. For example, a creep strain versus log t curve obtained under a given load at 60 °C and which terminates in rupture can be shifted to longer times. Needed to accomplish this are creep strain curves at, say, 20 °C and 40 °C under the same load. The lower temperature curves can be terminated before rupture provided that sufficient data are available to effect the TTS procedure properly. Because of the scatter in initial strains mentioned previously, the strain tests should be replicated.

In the SIM, which is a special case of TTS, the temperature of the creep test is raised in a series of steps. The sections of creep curve at the individual temperatures are then combined to form a continuous determination of the creep strain at the starting temperature. The time to rupture can also be determined. ASTM D 6992:2003 is recommended.

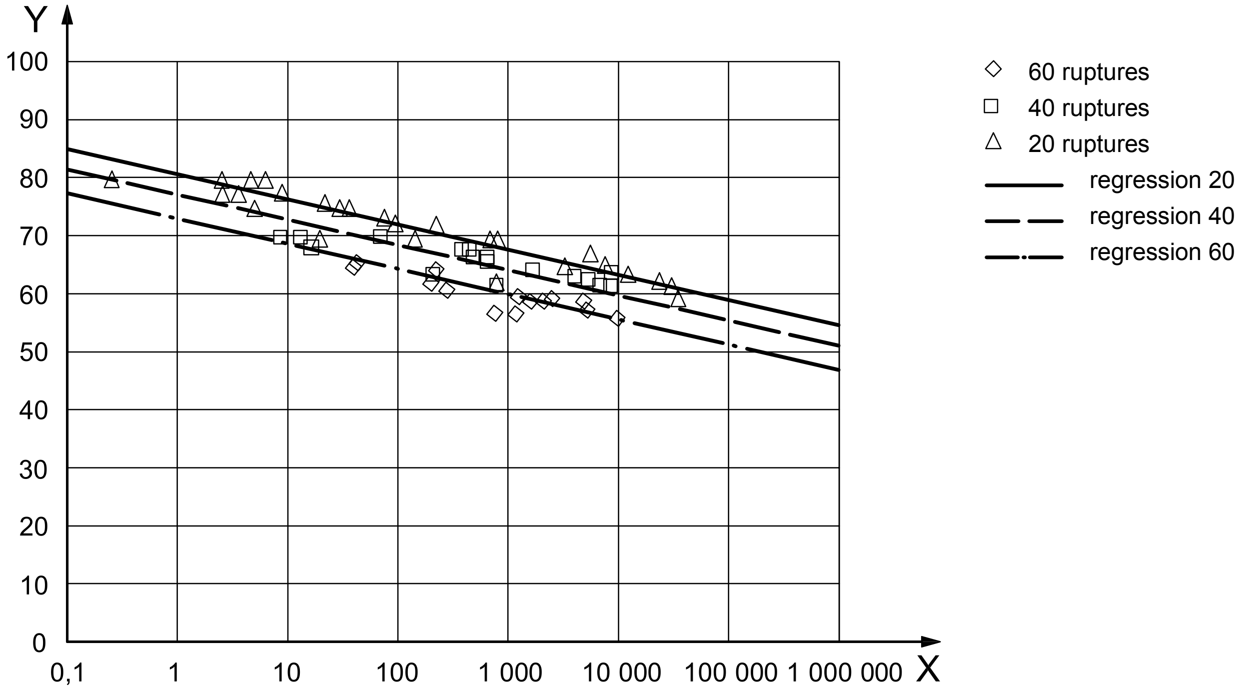
SIM can be considered for use in generating and extrapolating geosynthetic creep rupture data, provided that the predictions are consistent with those based on conventional testing or time-temperature block or strain shifting as described above. To this end, it is recommended that a minimum of 12 data points, time-shifted to the reference temperature, be obtained from accelerated (TTS and SIM) and conventional testing, with a minimum of

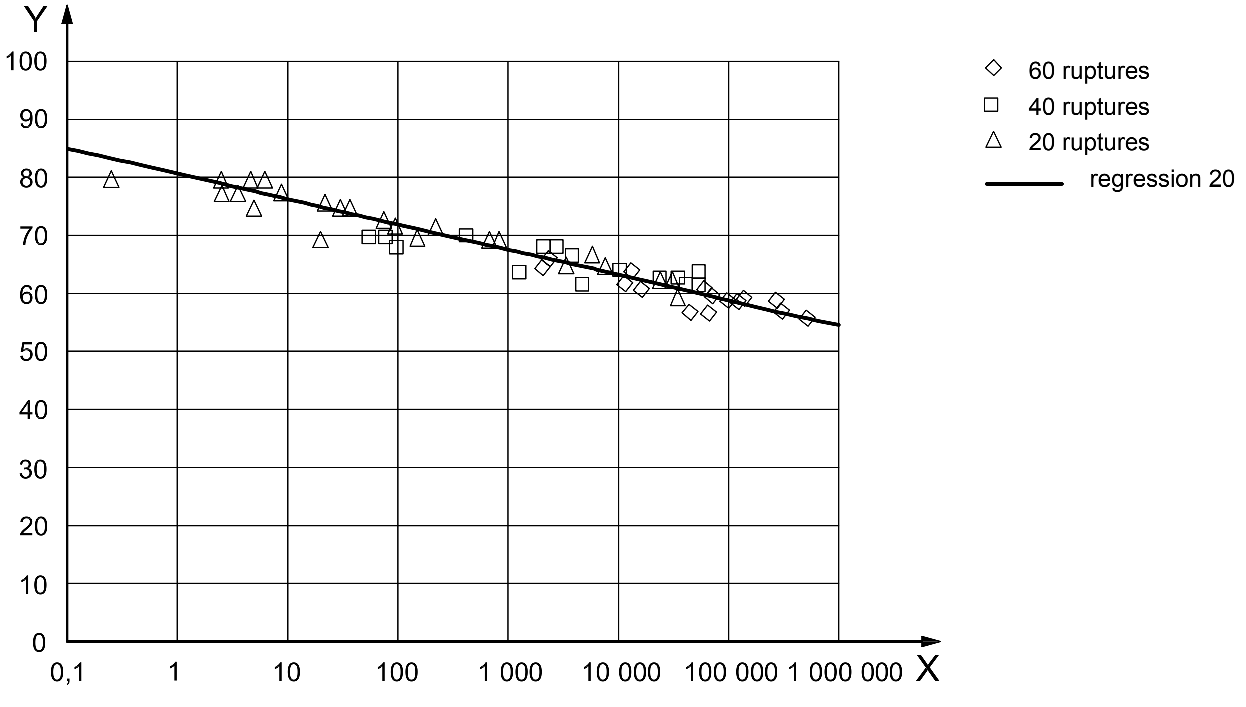
- three time-shifted durations between 1 000 and 100 000 h, and
- three time-shifted durations between 100 000 and 10 000 000 h.

In addition, a limited programme of conventional creep rupture tests obtained at the reference temperature and therefore un-shifted (except as corrected per 7.2), should be performed in accordance with 7.2. It is recommended that there should be four conventional creep rupture data points between 100 h and 10 000 h and one data point at 10 000 h or more. (The last data point may be an incomplete test). This conventional creep rupture data envelope should then be compared to the envelope determined from the accelerated data.

Linear regression analysis should be performed separately for the conventional and accelerated data in accordance with 7.3 and 7.4. The value of $\mathrm{RF}_{\mathrm{CR}}$ determined from the accelerated data at 2 000 h at the reference temperature should differ from the value of $\mathrm{RF}_{\mathrm{CR}}$ determined from conventional data at 2 000 h at the reference temperature by no more than 0,15. Also the value of $\mathrm{RF}_{\mathrm{CR}}$ determined from the accelerated data at 10 000 h at the reference temperature should differ from the value of $\mathrm{RF}_{\mathrm{CR}}$ determined from conventional data at 10 000 h at the reference temperature by no more than 0,15. If both the conditions are fulfilled, the SIM data may be combined with the conventional data and used to determine $\mathrm{RF}_{\mathrm{CR}}$. If not, $\mathrm{RF}_{\mathrm{CR}}$ should be determined from data from conventional testing alone (additional conventional data will be needed in this case).

The validity of SIM is supported by various publications [5-9] in the Bibliography.





Key

X Time (h)

Y Percentage tensile strength

Figure 6 — Block shifting

7.6 Extrapolation and definition of reduction factor or lifetime

Extrapolate the straight line fit to log t_D. Read off the corresponding percentage y from the formula $y = y_o - (\log t_D)/m$ (if y is a different function of load, derive the percentage accordingly).

Calculate $RF_{CR} = 100/y$. RF_{CR} should be greater than unity.

A condition of the extrapolation is that there is no evidence or reason to believe that the rupture behaviour will change over this duration. It should be checked that at long durations, and at elevated temperatures, if used:

- there is no abrupt change in the gradient of the creep rupture curve;
- there is no abrupt change in the strain to failure;
- there is no significant change in the appearance of the fracture surface.

Any evidence of such changes, particularly in accelerated tests, should invalidate the extrapolation unless it can be taken into account as described in the following example. Particular attention is drawn to the behaviour of unoriented thermoplastics under sustained load, where a transition in behaviour is observed in long-term creep rupture testing. The effect of this transition is that the gradient of the creep rupture curve steepens at the so-called “knee” such that long-term failures occur at much shorter lifetimes than would otherwise be predicted. The strain at failure is greatly reduced and the appearance of the fracture surface changes from ductile to semi-brittle. If this is observed, any extrapolation should assume that the “knee” will occur. For the method of extrapolation, reference should be made to ISO 9080:2003.

7.7 Residual strength

Creep rupture is Mode 3 degradation, resulting in little reduction in strength until the duration approaches the design life (see Figure 4). If the applied load is expected to be lower than T_{char}/RF_{CR}, it can be more appropriate to calculate the time to failure corresponding to the applied load and to check that this substantially exceeds t_D. On the basis of current measurements, it may then be assumed that the strength remains close to T_{char} over the design life. This is particularly relevant to seismic design and to other cases where a certain reserve strength has to be assured.

7.8 Reporting of results

The results should be reported as a graph of applied load (or a function of applied load) plotted against time to rupture in the manner of Figure 5.

The following should be stated:

- material;
- design lifetime;
- design temperature;
- T_{char};
- equation of the regression line $y = y_0 - x/m$;
- RF_{CR}.

7.9 Procedure in the absence of sufficient data

Long-term creep data obtained from tests performed on older product lines, or other products within the same product line, may be applied to new product lines, or a similar product within the same product line, if one of the following conditions is met.

- The materials and structure of the proposed product are similar to those of the tested product. Data should be provided which shows that the minor differences between the tested and the untested products will result in equal or greater creep resistance for the untested products.

- The results of a limited testing programme on the proposed product are not significantly different from those predicted from the data on the tested product. For creep evaluation, this limited testing programme should include creep tests taken to at least 1 000 h to 2 000 h in length.

- If SIM is accepted for the previously tested product, then SIM can be used exclusively on the proposed product or products. In this case, the SIM tests should be concentrated in the 100 000 h to 10 000 000 h time window for maximum statistical efficiency. Three SIM tests should be sufficient for each proposed product.

Similarity can be judged on the following.

- Equivalence of polymer structure, molecular weight, carboxyl end group count (CEG) cross-linking, crystallinity and draw ratio. It should be noted that per cent crystallinity is not a controlled property and there is presently no indication of what an acceptable value for percent crystallinity should be. For the method of determining CEG, see 9.4.5.2.

- Tensile strength per identifiable unit such as single rib or yarn. Tests performed on single ribs or yarns should, however, be shown to be representative of the material as a whole.

- Polymer additives used (i.e. type and quantity of antioxidants or other additives used).

- Textile (weave, style of non-woven, grid) and yarn structure, and fibre diameter.

NOTE Not all properties apply to all materials.

The data provided should show that the performance of the new or similar product is equal to or better than the performance of the product previously tested. If so, the results from the full testing programme on the older or similar product could be used for the new/similar product. If these conditions are not met, then a full testing and evaluation programme for the new product should be conducted.

Single ribs for geogrids or yarns for woven geotextiles may be used for creep testing for ultimate limit state design provided that it can be shown, for example, by a creep testing programme similar to the conventional creep tests defined in 7.5, that the rupture behaviour and envelope for the single ribs or yarns are the same as that for the full product.

If the procedures described in this section are applied, then this should be noted in the statement of the corresponding reduction factors.

8 Installation damage

8.1 General

Coarse backfills and heavy compaction loads can damage geosynthetics, causing an immediate reduction in strength. The effect is referred to as installation damage and the corresponding reduction factor as RF_{ID}.

Generally, the mechanical damage occurs on installation (Mode 1). If significant further damage is likely to occur in use, there will be an additional time-dependent contribution to this factor.

8.2 Data recommended

Measurement of the effect of installation damage on geosynthetic reinforcement strength and deformation should be determined from the results of installation damage tests. General guidance is given ISO 13437 and BS 8006,1995, Annex D. The installation damage tests should simulate the installation conditions (conditions of service) as closely as practicable to the installation conditions anticipated in the geosynthetic structure. The installation conditions to be simulated should include, as a minimum:

- the nature of the backfill both below and above the sample: particle size distribution, hardness and angularity;
- the depth at which the sample is installed;
- whether the material is driven over by vehicles before compaction;
- method and degree of compaction.

Test results from damaged specimens should be compared to tensile test results obtained from undamaged (i.e., not exposed to installation conditions) specimens taken from the same lot, and preferably the same roll, of material as the damaged specimens.

The specimens should be large enough to be used for wide-width tensile testing (ISO 10319). Consideration should be given to increasing the number of specimens to ensure that they are fully representative of the damaged material. It is desirable that multi-rib tests, with at least four ribs, should be used for installation damage evaluation. With single rib testing it can be difficult to assess the effect of severed ribs on the strength and modulus of damaged materials, and the effect of differences in degree of damage between ribs on the overall tensile strength of the product. Single ribs of geogrids are generally unsuitable for installation damage testing. If this cannot be avoided, for example, for very high strength materials, then it should be demonstrated that the strength of the single ribs is representative of the full product.

Further information is given in [10] in the Bibliography.

8.3 Calculation of reduction factor

The reduction factor to allow for the effect of mechanical damage for the site conditions used, RF_{ID}, should be expressed as the ratio of the mean tensile strength of the undamaged material to the mean tensile strength of the damaged material.

8.4 Procedure in the absence of direct data

8.4.1 General

In the absence of site-specific data obtained in accordance with 8.2, one of the approaches in 8.4.2, 8.4.3 or 8.4.4 can be taken.

8.4.2 Interpolation from measurements with different soils

If the RF_{ID} of the material under consideration is known for other soils with grain size both less than and greater than the soil to be used, then RF_{ID} should be determined by interpolation using the values of d_{50} or an alternative such as d_{90} for the respective soils to obtain RF_{ID} for the soil in question. It is recognized that this is only an approximation, particularly for soils with a broad particle distribution, and other soil gradation characteristics may be considered for interpolation purposes if it can be shown that they produce a more accurate correlation than the d_{50} size. An example of this interpolation procedure to obtain RF_{ID} at a different soil d_{50} is provided in Figure 7, which shows the interpolation of RF_{ID} for a soil with d_{50} equalling 2 mm from measurements made with soils with d_{50} equalling 0,02 mm, 0,5 mm and 10 mm.

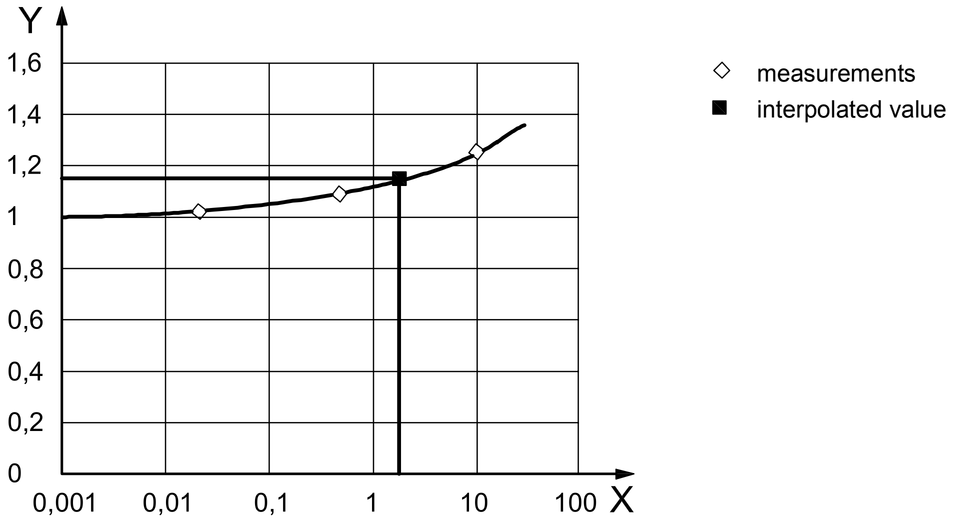
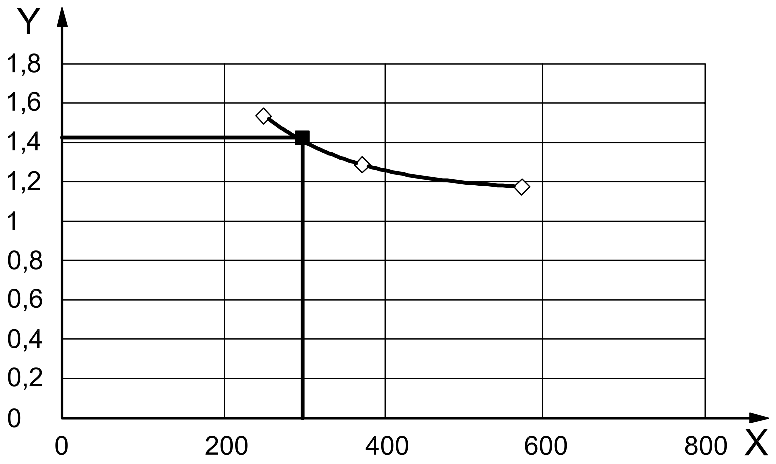


Figure 7 — Interpolation of RF_{ID}

8.4.3 Interpolation between products of the same product line

This interpolation may also be made for other products within the product line of the subject product, provided that a relationship can be established between the weight, tensile strength, etc. of the product and the RF_{ID} of the product as in Figure 8, and provided that data are available for products which are both lighter (weaker) and heavier (stronger) than the product in question. For products that are heavier (stronger) than the heaviest product tested, the RF_{ID} for the heaviest product tested may be used. For coated polyester geogrids, the coating thickness or coating mass per area relative to the mass per area of the product should be considered for the purpose of correlating RF_{ID} between products rather than product weight or tensile strength alone. In Figure 8 for a product of weight 300 g/m^2, RF_{ID} = 1,42.



Key

X Product weight, g/m^2

Y Reduction factor RF_{ID}

Figure 8 — Interpolation of RFID from damage measurements on products from the same line but with different weights

8.4.4 Laboratory damage tests

It should be noted that ISO 10722 is intended as an index test for comparative purposes and should not be used for the derivation of reduction factors for geosynthetic soil reinforcements.

9 Weathering, chemical and biological degradation

9.1 Introduction

Polymers are susceptible to environmental degradation due to weathering, including exposure to ultraviolet light, to chemical attack and to biological attack. All three effects are further influenced by temperature and, for some polymers, by moisture uptake. The durability of geosynthetic reinforcements is improved by their high degree of orientation and high molecular weights, while for polyolefins in particular the principal reason is the inclusion of special additives.

Environmental degradation can lead to degradation by Modes 1, 2 and 3. Weathering on site before a geotextile is covered can be regarded as Mode 1, while the weathering of geotextiles permanently exposed should be regarded as Mode 2. For chemical degradation, the preferred approach is to restrict the service lifetime to the period over which no significant reduction in strength is predicted. This is, however, not always possible, and for the hydrolysis of polyesters, which takes place continuously (Mode 2) a time-dependent reduction factor should be determined.

Two reduction factors are defined: RF_W for weathering and RF_{CH} for chemical and biological degradation. Allowances for statistical scatter and uncertainty are made by means of a separate factor of safety, f_s.

9.2 Data recommended for assessment

It is recommended that the following data be provided.

- Statement of principal polymers used.
- Evidence of the resistance of these polymers to weathering (for example EN 12224) and to chemical degradation, in particular to hydrolysis and oxidation in aqueous solutions with or without the presence of oxygen. For polyesters, a statement may be made of the number averaged molecular weight (M_n) and of the carboxyl end group count (CEG).
- A statement that post-consumer recycled material is not used.
- Predicted exposure to daylight: duration, location and season.
- Effective design soil temperature (see 4.4).
- Soil pH.
- A statement of any non-natural contaminants in the soil, e.g. industrial waste.
- Any unusual biological hazards such as termites.

9.3 Weathering

All polymers can degrade when exposed to ultraviolet light, although stabilizing additives will normally have been added to materials intended for outdoor use. In this Technical Report, “weathering” will be taken as applying solely to the effects of ultraviolet light, either alone or together with temperature and water spray.

The recommendations for weathering are related to the duration of exposure during storage and on site. If the geosynthetic is exposed to ultraviolet light for a maximum of 12 h, no reduction factor need be applied. If the exposure time is longer, then the geosynthetic should undergo an accelerated weathering index test such as

EN 12224. If the loss of strength is no greater than 5 % or is not statistically significant, no reduction factor is applicable. This is on condition that the installer covers the geosynthetic within one month.

Any geosynthetic reinforcement showing a greater loss of strength should not be exposed on site for longer than the duration shown in Table 1, and a reduction factor RF_W should be applied.

Table 1 — Installation exposure period

Retained strength after testing according to EN 12224	**Maximum exposure time (uncovered) during installation**	**Reduction factor** RF_W
$>$ 80 %	1 month [a]	Ratio of tensile strength of unexposed material to that of exposed material
60 % to 80 %	2 weeks	1,25
$<$ 60 %	1 day	1,00
Untested material	1 day	1,00

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

For a range of products identical except for mass per area, it is sufficient to subject only the product with the lowest mass per area to the test. The results of the test may be applied for the other products in the range, unless they have been tested separately.

If the geosynthetic is to be exposed to light for longer than one month, then it should be tested according to EN 12224 or a similar method for a duration such that extrapolation of the radiant exposure to that expected in service can be justified. The radiant exposure (ultraviolet radiation) in EN 12224 is 50 MJ/m^2, corresponding to approximately one summer month's exposure in southern European or central North American latitudes. The strength retained after the full radiant exposure should be predicted. RF_W should be set equal to the ratio of the strength of the unexposed material to that predicted for the exposed material.

9.4 Chemical degradation

9.4.1 Causes of chemical degradation

The principal causes of chemical degradation of polymeric geosynthetics in the soil are described in ISO/TR 13434. The following is a summary.

The principal cause of degradation of polyester geosynthetics (which consist of polyethylene terephthalate (PET) is by hydrolysis. The rate of hydrolysis is slow at typical soil temperatures but increases rapidly as the temperature is raised. The rate can be less if the polyester is fully coated, but this is discounted since the coating may become damaged by the installation process in the ground. Since PET wicks moisture quite well, any exposure of the fibres due to coating damage could result in hydrolysis at the rate which would occur if the coating was not present. The rate of hydrolysis will be less if the soil is partially instead of fully saturated, but is not zero. Alkaline liquids with $pH \geqslant 9$ can, in addition, erode the surface. Polyester reinforced geosynthetics should not be used in natural or industrially polluted soils where $pH > 9$ is maintained unless proof of their durability can be provided.

The principal cause of degradation of polypropylene and polyethylene is oxidation, also resulting in chain scission, reduced molecular weight and strength loss. Other effects are embrittlement, surface cracking and a change in colour. Oxidation of these materials is a chain reaction whose chemistry is complex but quite well understood. The reaction may be started by ultraviolet light or by heat, and may be accelerated by catalysts such as ions of heavy metals, including iron. The resistance of these materials to oxidation is improved dramatically by the addition of a selection of antioxidant stabilizers which can extend the lifetime by hundreds or thousands of times. Ultimately, the antioxidant is consumed by oxidation, if it has not been lost prematurely by migration, evaporation or leaching. Assessment of the rate of oxidation is complex and is further described in 9.4.4.

Polyamides can degrade by either mechanism. Aliphatic polyamides such as PA 6 are susceptible to thermal degradation, oxidation, ultraviolet radiation, acid or alkali attack causing chain scission and by hydrolysis through contact with water at elevated temperatures. They are stabilized by copper salts, aromatic amines and hindered phenolic antioxidants which all act as heat stabilizers. Hindered phenol antioxidants are the most effective as they also resist thermoxidative degradation. Aromatic polyamides such as aramids are more resistant than PA 6 to degradation by oxidation, acids, alkalis and hydrolysis but are susceptible to ultraviolet degradation. Stabilization of these polyamides is effected by adding chlorine and nitro substituents into the recurring structural unit of the polymers.

Lifetime prediction can be based on evidence from service or from accelerated testing. In some cases, there is sufficient experience to define index tests that will assure a certain minimum level of durability.

9.4.2 Evidence from service experience

The rate of degradation, or evidence for lack of degradation, can be based on results of analysis of specimens of the product exposed to a comparable environment and then exhumed, or of products with a similar physical structure and chemical formulation and including the same additives.

The plan of exhumation and testing should be in accordance with ISO 13437. The following additional points should be noted.

- The observation period should be of sufficient length for extrapolation to the full design life to be justified. This justification is particularly important when rapid degradation follows a long incubation period, or when degradation takes place in a series of separate stages (e.g. 9.4.4.3). Service experience of at least 10 years may be necessary for extrapolation to a service life of 50 to 100 years for PET geosynthetics. Longer periods of time may be needed for polyolefins due to the presence of antioxidants, as no loss in strength will be observed until the antioxidants are used up. Without knowing how long this will take, it is impossible to predict lifetime.

- Generally, a minimum of three retrievals are to be made (i.e., the first retrieval is taken right after installation, the second retrieval is taken at some time during the middle of this period, and the third retrieval is taken at the end of the study period).

- Enough specimens for each retrieval should be taken into account for statistical variability in the properties measured. For a more detailed description, see [11] in the Bibliography.

- The polymer and physical characteristics of the exhumed material should meet the recommendations for “similar” products in 7.9.

An assessment and lifetime prediction should then be made on the basis of this evidence. For a more detailed description of the issues that should be considered when evaluating results from service experience, see [2], [11] and [12] in the Bibliography.

9.4.3 Accelerated chemical degradation tests

The rate of degradation can be estimated using accelerated testing, in which either temperature or chemical concentration, or both, is increased in order to accelerate the rate of reaction. The relation between the rate of degradation under service conditions to that during accelerated testing can be derived from chemical rate kinetics or from Arrhenius’ equation. Take care that the conditions during the accelerated tests are representative of those in service. There should be no change in the mechanism of degradation or in the physical structure of the material; and no barrier layers should form or be present that might retard the degradation process in a manner that does not occur in service.

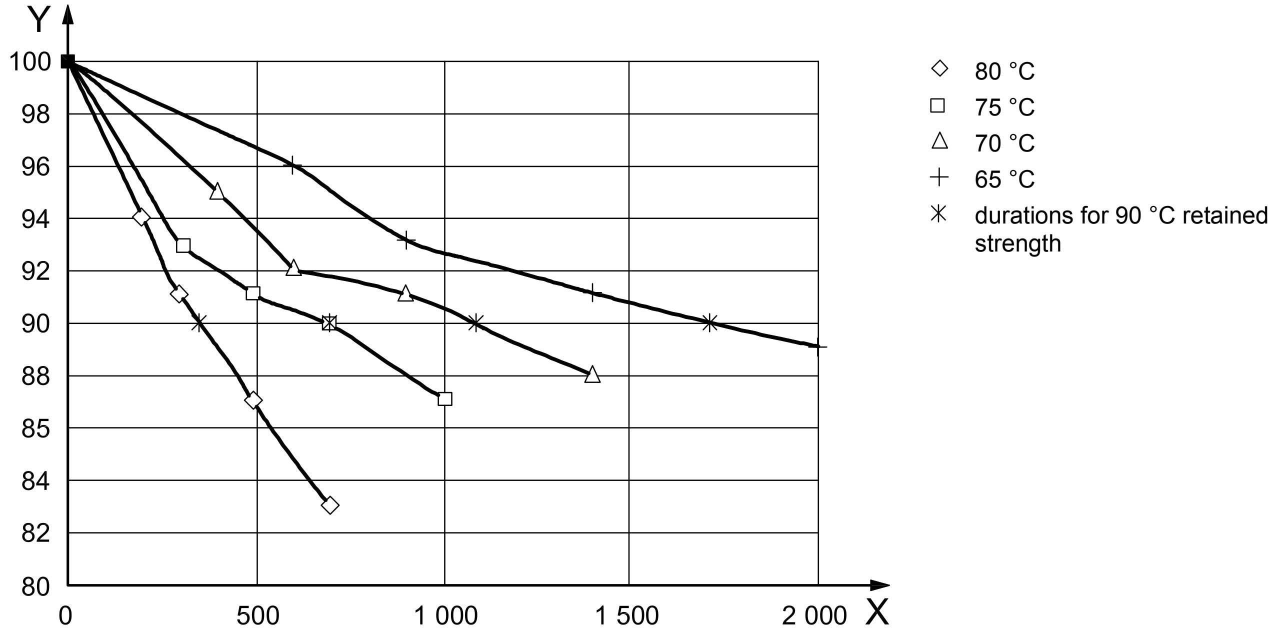
In such a programme, carry out the following procedures.

- Select the parameter to be measured, for example, a level of retained strength such as 90 %, 80 %, 70 %, 60 % or 50 %. If experience has shown that another physical or chemical quantity, such as CEG, gives more precise results, then this may be used instead, provided there is an established relationship between the parameter measured and the strength. It is important that the degradation can be observed and measured; if not, the degree of acceleration cannot be ascertained.

- Decide on the environment: pure water, air or a special chemical environment. If the geosynthetic is to be placed in a natural soil with pH < 4 or > 9, or in a soil with non-natural contaminants, e.g. industrial waste, immersion tests should be performed in liquids with corresponding chemical composition and extrapolated to the corresponding design soil temperature, chemical composition and service life. ISO/TR 12960 describes a method of immersion. In testing with alkaline solutions, care should be taken to reduce conversion of hydroxide to carbonate ions by reaction with atmospheric carbon dioxide.

- Select a range of at least three to four temperatures, spaced typically at 10 °C intervals. The lowest test temperature should ideally be not more than 25 °C above the service temperature, allowing for the fact that the test duration at this temperature has to lie within the time-scale of the test programme. This can extend for as long as four years. Caution is advised if any transition occurs in the physical state of the polymer or the mechanism of degradation less than 10 °C above the highest test temperature, or between the lowest test temperature and the service temperature. A glass transition occurs in the range of 50 °C to 80 °C in polyester and crystalline melting in high density polyethylene (HDPE) takes place at a range of temperatures, peaking at 128 °C. Furthermore, drawn polyethylene tends to lose its orientation at temperatures of around 70 °C. If a transition is present, then it should be demonstrated that it leads to no significant change in the rate of degradation, for example by confirming that the Arrhenius plot is a straight line.

- Measure the reduction in strength (or other parameter) over time at each of a range of temperatures. To do this, expose groups of samples over a range of times at each temperature. Include spare sets for exposure over longer times in case the rate of reduction in strength is less than predicted. Note that full wide-width specimens are preferred for this testing; however, single rib or yarn specimens can be used if necessary. Plot the retained strength against time and determine either the rate of change or, by interpolation, the exact times to the desired retained strength (Figure 9). In Figure 9, the durations for 90 % retained strength are interpolated from the lines, noting that these are often irregular in shape. Examine each test sample for any change in the nature of degradation or of failure, for example, the growth of a barrier layer on the surface or circumferential cracking on the fibre surface, or increased ductility as evidenced by the geosynthetic modulus and peak strain at the higher temperatures. Scanning electron microscopy is a useful aid to this purpose. If a change is observed, only those results should be retained which are regarded as being representative of long-term degradation. If process of degradation comprises two or more separate stages, separate extrapolations should be made for each stage.



Key

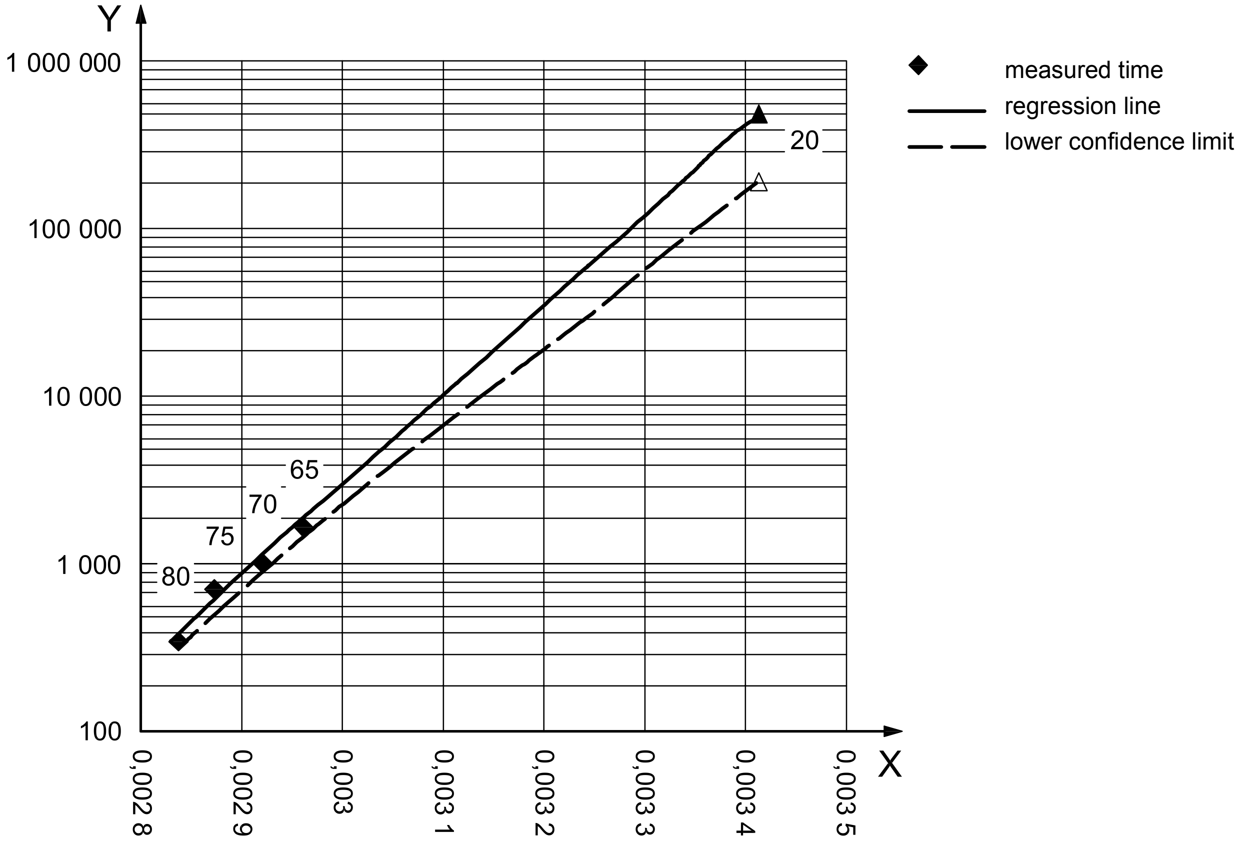
X Time (h)

Y % retained strength

Figure 9 — Reduction in strength at selected temperatures prior to application of Arrhenius' formula

- The number of specimens taken at each retrieval for testing may need to be greater than what is required for testing of the unaged material. This is because the degradation may lead to additional variability in the strength.

- Plot the times to a particular retained strength or other parameter against the inverse of the absolute temperature θ_K in K (see Figure 10). If Arrhenius' formula applies this plot should be a straight line. If it is not a straight line, then the order of the chemical reaction may be different (for the procedure, see [13] in the Bibliography, or a transition may have occurred within the range of test temperatures selected as discussed above. If no straight line is obtained, then Arrhenius' formula does not apply and extrapolation is invalid.



Key

X Inverse absolute temperature (1/K)

Y Time to 90 % retained strength (h)

Figure 10 — Arrhenius diagram

- Calculate the equation of the straight line, with $y = \log t_{90}$ and $x = 1/\theta_j$, as:

$$y = \bar{y} + b_a (x - \bar{x})$$

where

$b_a = S_{xy}/S_{xx}$;

$S_{xx} = \Sigma (x - \bar{x})^2$;

$S_{yy} = \Sigma (y - \bar{y})^2$;

$S_{xy} = \Sigma (x - \bar{x})(y - \bar{y})$.

— Calculate the lower confidence limit (LCL) of the line:

$$y = \bar{y} + b_\mathrm{a} (x - \bar{x}) - t_{n-2}\, \sigma_0 \sqrt{[1 + 1/n + (x - \bar{x})^2/S_\mathrm{xx}]}$$

where

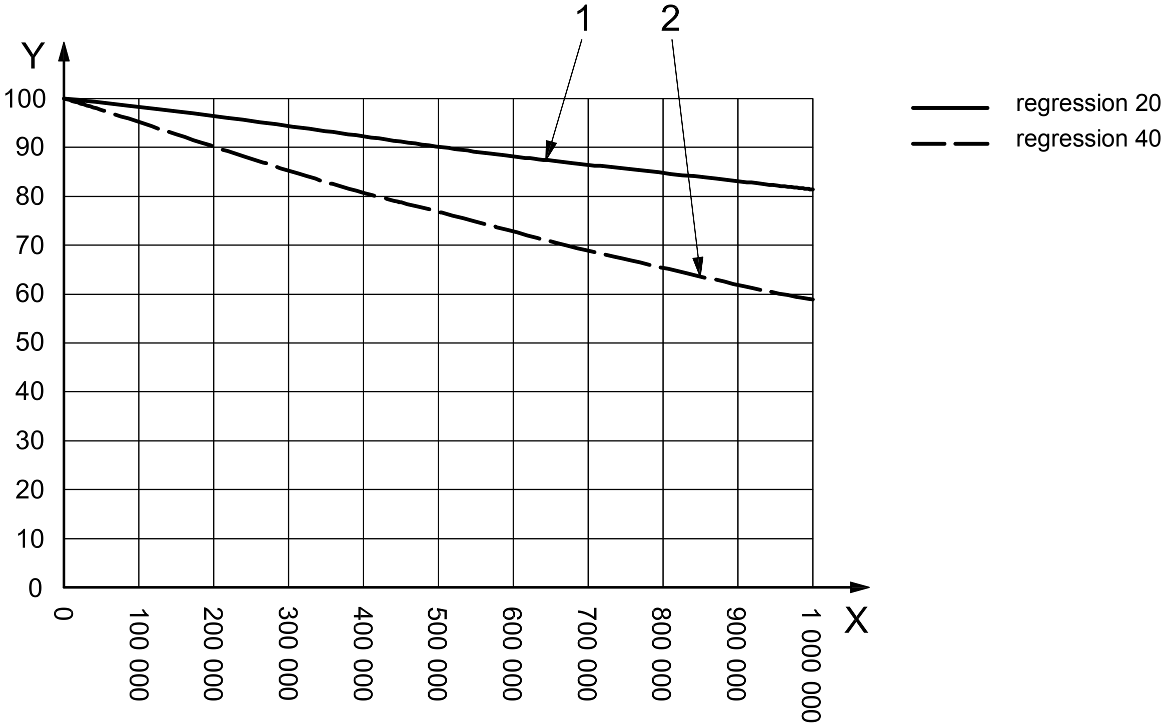
t_{n-2} is the Student's t for $n - 2$ degrees of freedom and a stated probability;

n is the number of Arrhenius points;

σ_0 is the $\sqrt{[(S_\mathrm{yy} - S_\mathrm{xy}{}^2/S_\mathrm{xx})/(n - 2)]}$.

— Plot these lines as in Figure 10; from the regression line read off the time t_s to the defined retained strength at the service temperature $x = 1/\theta_\mathrm{s}$ (noting particularly if this exceeds 25 °C); from the lower confidence limit read off the time t_LCL; in Figure 10, these two values are 516 000 h and 199 000 h respectively. Such large differences are typical of logarithmic scales.

— Using the shape of the observed degradation curves as a guide, plot the shape of the degradation curve such that the defined retained strength is reached after time t_s (Figure 11). Read off the unfactored long-term strength per width T_x (expressed as a percentage of the batch tensile strength) after the design life t_D. $\mathrm{RF}_\mathrm{CH} = 100/T_\mathrm{x}$. Make a similar plot for t_LCL and derive the LCL T_LCL. The ratio $R_2 = T_\mathrm{x}/T_\mathrm{LCL}$. In Figure 11, 90 % retained strength is reached at the predicted duration for the service temperature – in this example, 90 % after 516 000 h. The predicted strength after 1 000 000 h is 81,5 % and the RF_CH = 100/81,59 = 1,23. A similar derivation is carried out for the LCL for which the predicted strength after 1 000 000 h is 58,8 %. The ratio R_2 = 81,5/58,8 = 1,39.



Key

X Time (h)

Y % retained strength

Figure 11 — Degradation curve at the service temperature

Further guidance is given in IEC 60216 and in [2], [11], [13] and [17] in the Bibliography.

9.4.4 Oxidation of polyolefins

9.4.4.1 General

There are currently three approaches to the assessment of the oxidation resistance of polyolefins: simple Arrhenius testing, multiple Arrhenius testing and pressurized oxygen testing.

9.4.4.2 Simple Arrhenius testing

Historically, overall lifetime has been predicted by treating the entire oxidation process as a single stage. Time to end of life is measured at different temperatures and extrapolated to the service temperature to define the service life, or to the service life to define the operating temperature (e.g. see IEC 60216). The degradation of polypropylene fibre can be extremely sudden and thus give an indication of lifetime prediction. However, the methods have suffered from inaccuracies due to the following.

- The antioxidants present delay the onset of oxidation of the main polymer, causing the reaction rate with oxygen to change over time for the material.
- The oven temperature should stay well below the melting temperature of the polymer, thus restricting the exposure temperatures to a narrow range.
- The mechanism of oxidation can change at higher temperatures, invalidating the extrapolation.
- The different rates of degradation described above can lead to large errors in the measurement of time to end of life and of its extrapolation.
- Surface cracking has been observed in certain grades of polypropylene. This increases the access of oxygen to the polymer and invalidates any prediction based on uncracked material; furthermore, at elevated temperatures, these cracks can heal, which will possibly occur at lower temperatures.
- Diffusion of antioxidants plays a major part at all stages of oxidation. The rate of diffusion of oxygen from the outside, the rate of diffusion of antioxidants and the rate of migration of radicals produced by the chain reaction all increase at higher temperatures and decrease with crystallinity and orientation of the polymer. These effects are accelerated by a high surface-to-volume ratio. Hence, a high surface-to-volume ratio and a low degree of orientation will clearly shorten all stages of oxidation.
- Leaching may also occur in materials having a high surface-to-volume ratio or containing leach-sensitive antioxidants. For these materials, correct selection of stabilizers is essential.

Polyethylene and polypropylene geotextiles cover a wide range of structures from fine, highly oriented fibres to thick and less strongly oriented polymeric geosynthetic barriers. They contain different combinations of antioxidants. Some exhibit surface cracking. In polymeric geosynthetic barriers and the less oriented areas of extruded geogrids, the rate of oxidation should be higher due to the lack of orientation, but simultaneously lower due to the small surface-to-volume ratio.

This explains why it has proved impossible to define a single oven ageing test as a screening test for all geosynthetics. Various attempts to do so have either failed to eliminate poorly stabilized material or conversely have eliminated material which would be expected to be durable. Better results can be obtained by restricting the temperature to 80 °C or below, by dividing the process into stages of oxidation or by raising the oxygen pressure as in ISO 13438.

9.4.4.3 Multiple Arrhenius testing

The degradation of a stabilized polypropylene or polyethylene can be divided into two stages: consumption of the antioxidant, and degradation of the unprotected polymer. To establish which stage has been reached, use is made of oxidation induction time (OIT) measurement or high pressure oxidation induction time (HPOIT) where hindered amine light stabilizers (HALS) are present. OIT cannot be applied universally because it only relates to antioxidants active at the testing temperature, which is in the molten state. In these methods, a sample of material is raised to a high temperature in an inert atmosphere, pure oxygen is admitted and the time to oxidation measured thermally by differential scanning calorimetry (DSC). For materials in the first stage of oxidation, the OIT reduces progressively as the antioxidant is consumed, but the mechanical properties remain unchanged. In the second stage, the OIT is low and the mechanical strength and elongation at break diminish. It is possible that the antioxidants intended to increase the durability are only effective at lower temperatures. It should be recognized that this two-stage procedure is a simplified model.

Accelerated oxidation testing is performed by heating the geosynthetic in a forced air oven. For details of representative methods and equipment, see IEC 60216. Sets of specimens should be exposed at different test temperatures as described in 9.4.3, but separate estimates should be made for the different stages described above:

- t_{ind}: the induction time during oxidation, i.e. the duration of the first stage over which mechanical strength does not change, but OIT can drop;
- t_{deg}: the degradation time during oxidation, i.e. duration of the second stage until the set retained strength is reached.

Make separate Arrhenius plots for t_{ind} and t_{deg}. Examine all specimens for examples of surface cracking (this can require the use of a scanning electron microscope with a magnification of 4 000 x) and eliminate those where the cracking can be shown to accelerate the oxidation process.

If a reduction in strength can be accepted, estimate the total lifetime (t_{ind} + t_{deg}) for each set retained strength and plot retained strength against total lifetime. Read off, by interpolation, the retained strength for the service lifetime at the service temperature. Set RF_{CH} equal to the reciprocal of the retained strength.

NOTE Testing under oxygen pressure. Raising the availability of oxygen by using pure oxygen gas under pressure presents an alternative method of acceleration [13] and [18] in the Bibliography. It compensates the distortion of rate of oxidation found by limiting oxygen diffusion in products with a high surface-to-volume ratio in oven testing at elevated temperatures and accelerates oxidation to a certain degree due to a higher oxygen concentration in all the materials. Furthermore, the test can be performed with the geosynthetics suspended in an aqueous phase in order to simulate leaching effects, which could be especially serious for materials with a high surface-to-volume ratio. Such a test is specified in ISO 13438. Correlation of this test with long-term durability has not yet been completed.

9.4.5 Hydrolysis of polyesters

9.4.5.1 General

An assessment of the rate of degradation, or evidence of lack of degradation, should be made according to 9.4.2 or 9.4.3. For a laboratory assessment based on 9.4.3, particular attention should be paid to the following:

- testing should consist of elevated temperature immersion tests to evaluate potential for hydrolysis effects in water or a specific solution to evaluate a specific environment;
- the reactor should be capable of maintaining temperature uniformity (± 1 °C) and stability during long-term use;
- at least three temperatures below the physical transition of polyester at 70 °C to 80 °C should be included: if a change in the gradient of the Arrhenius curve is observed in this temperature range then results from testing at higher temperatures should be excluded from the extrapolation;
- specimens should be suspended in the solution on a hanger made of a material that will not react with or contaminate the immersion fluid and specimens [e.g. polytetrafluorethylene (PTFE), HDPE, stainless steel];
- the specimens should be free to contract in either direction and not framed to prevent shrinkage;
- the tests should be performed on the uncoated yarns, strips or fabric;

- the solution should be intensively stirred to ensure solution uniformity;
- the pH should be monitored and the liquid replaced if the pH $>$ 8.

The assessment should predict either

- no statistically significant reduction in strength during the service life. In this case $\mathrm{RF}_{\mathrm{CH}}$ equals 1, or
- a reduction in strength with time. In this case, $\mathrm{RF}_{\mathrm{CH}}$ should equal the ratio of the strength of the unexposed material to the predicted strength for the design life t_{D}.

In both cases, the assumed ambient conditions such as soil temperature and pH should be stated.

Predictions based on accelerated testing are subject to a level of uncertainty. This is taken into account in the ratio R_2 which contributes to the factor of safety f_{s}. The method for calculating R_2 is described in 10.1.

A geosynthetic that comprises more than one polymer should be subject to a separate assessment for each polymer.

For a range of products identical except for mass per area, then initially only the product with the lowest mass per area should be subjected to the test or assessment procedure. The value(s) of $\mathrm{RF}_{\mathrm{CH}}$ assigned to this product may then be applied to the other products in the range.

For further information, see [11] and [19] in the Bibliography.

9.4.5.2 Index tests for polyesters

The long-term chemical durability of polyesters in relatively neutral aqueous environments can be tested by one of the following sets of index tests.

- The polyester geosynthetics used for reinforcement, or the yarns from which they are made, should exhibit no more than a 50 % reduction in strength when subjected to EN 12224.
- The CEG measured according to GRI-GG 7 should be less than 30 meq/g, and the number averaged molecular weight, M_{n}, determined according to GRI-GG 8 should be 25,000 or more. Both criteria should be satisfied.

NOTE A condition of both criteria is that the polyester contains no post-consumer or post-industrial recycled material.

For a geosynthetic that satisfies either recommendation used in saturated soil, estimated values of $\mathrm{RF}_{\mathrm{CH}}$ are listed in Table 2. Lower values may be considered when the soil is not saturated and/or if further evidence is provided.

Table 2 — Estimated values of $\mathrm{RF}_{\mathrm{CH}}$ for polyesters

pH range	Design lifetime (years)	Service temperature (°C)	$\mathrm{RF}_{\mathrm{CH}}$	R_2
4 to 9	25	25	1,0	1,0
4 to 8	100	25	1,2	1,0
8 to 9	100	25	1,3	1,0
4 to 9	25	35	1,4	1,0

9.4.5.3 Index test for polypropylene and polyethylene

The long-term chemical durability of polyolefins can be tested according to ISO 13438. If the retained strength exceeds 50 % when tested according to method A2 or C2 for polypropylene, or method B2 or C2 for polyethylene, then for 100 years at a service temperature of up to 25 °C a value of 1,3 is estimated for with R_2 = 1,0. Lower values for RF_{CH} may be considered if further evidence is provided.

9.4.6 Procedure in the absence of sufficient data

If RF_{CH} is based on data obtained from long-term service experience (see 9.4.2) or long-term chemical degradation tests (see 9.4.3) performed on older product lines, or other products within the same product line, RF_{CH} determined in this manner can be applied to new product lines, or a similar product within the same product line, if one or both of the following conditions apply:

- the materials and structure of the proposed product are similar to those of the tested product. Data should be provided which shows that the minor differences between the tested and the untested products will result in equal or greater long-term chemical durability for the untested products;
- the results of a limited testing programme on the proposed product are not significantly different from those predicted from the data on the tested product. For chemical durability evaluation, this limited testing programme should include tests taken to at least 2 000 h in length at a temperature just below any significant transition in durability behaviour. This approach should only be used for materials for which this testing will conclusively demonstrate the similarity or dissimilarity of the long-term durability of the material.

Similarity can be judged on the criteria listed in 7.9. Also note fibre surface characteristics (e.g. presence of surface cracking).

The data provided should show that the performance of the new or similar product is equal to or better than the performance of the product previously tested. If so, the results from the full testing programme on the older or similar product could be used for the new/similar product. If these conditions do not apply, then a full testing and evaluation programme for the new product should be conducted.

9.5 Biological degradation

Biological degradation has not proved a serious factor in the service life of geosynthetics. This is because the high molecular weight polyethylene, polyester, polypropylene and polyamide used are not easily broken down by bacteria and fungi. The high tensile strength of soil reinforcements prevents them from damage by roots and burrowing animals, such as rabbits. For this reason it is not in general necessary to consider biological degradation in calculating RF_{CH}. However, the possibility of biological degradation should be reviewed if new polymers other than those described are used, or an index test performed to EN 12225 indicates degradation is possible, or if there are unusual biological circumstances, e.g. termites. Certain additives have been known to be subject to biological attack, and if the function of the additive was to prevent, for example, oxidation, then without it the base polymer will be subject to more rapid degradation.

Biological attack, if it occurs, is believed to take place relatively rapidly (Mode 3). It is more appropriate to define a minimum period over which no biological attack is predicted to occur than to define a reduction factor.

10 Determination of long-term strength

10.1 Factor of safety f_{s}

A factor of safety should be applied to T_{char}. The purpose of the factor of safety f_{s} is to allow for extrapolation uncertainty, particularly in extrapolation over long durations.

To take into account uncertainty due to the extrapolation of the creep rupture data, set $R_1 = 1{,}2^{r-1}$ where $r = \log(t_{\text{D}}/t_{\text{max}})$ with a minimum value of 1,0. t_{max} refers to the duration of the longest observed time to creep rupture, expressed in h, after TTS if appropriate.

To take into account uncertainty due to the extrapolation of accelerated chemical data, it is recommended that $R_2 = T_x/T_{LCL}$ (see 9.4.3)

Set $f_s = 1 + \sqrt{((1-R_1)^2 + (1-R_2)^2)}$.

Lower values may be considered if further evidence is provided.

10.2 Design for residual strength

If the design is based on a sustained load together with the ability to withstand a temporary seismic or other overload, then the design lifetime should be a fraction (e.g. < 10 %) of the time over which the sustained load would lead to rupture. The residual strength at any point during this lifetime should then be taken to be

$$T_{DR} = T_{char}/(\mathrm{RF}_{ID} \cdot F_W \cdot RF_{CH} \cdot f_s)$$

11 Reporting

The final statement should include the items in Table 3.

Table 3 — List of items to be stated

Item	Symbol	Clause
Material	—	—
Design lifetime	t_D	4.2
Assumed soil conditions: gradation, angularity, saturation, pH, presence of contaminants, nature of compaction and fill depth both above and below the geosynthetic	—	—
Design temperature	θ_s	4.4
Isochronous diagram, if appropriate	—	5.4
Characteristic strength (per width)	T_{char}	6.1
Recommended maximum time of exposure to light	—	9.3
Reduction factor to allow for the effect of sustained static load	RF_{CR}	7.6
Reduction factor to allow for the effect of mechanical damage	RF_{ID}	8.3
Reduction factor to allow for weathering	RF_W	9.3 (Table 1)
Reduction factor to allow for chemical and biological effects	RF_{CH}	9.4.2 (service experience) 9.4.3 (accelerated testing) 9.4.4 (oxidation) 9.4.5 (hydrolysis)
Factor of safety	f_s	10.1
Long-term strength per width (including factor of safety)	T_D	$= T_{char}/(\mathrm{RF}_{CR} \cdot \mathrm{RF}_{ID} \cdot \mathrm{RF}_W \cdot \mathrm{RF}_{CH} \cdot f_s)$
Residual strength	T_{DR}	$= T_{char}/(\mathrm{RF}_{ID} \cdot \mathrm{RF}_W \cdot \mathrm{RF}_{CH} \cdot f_s)$

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