Geosynthetics, J. Kuwano & J. Koseki (eds)
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How to predict hundred year lifetimes for geosynthetics

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Keywords: durability, life prediction, accelerated testing

ABSTRACT: In contrast to most industrial applications of textiles and plastics, many civil engineering structures are expected to last for 100 years or more. However, the polymers used in geosynthetics were not even invented a century ago. This paper describes the procedures to be adopted in predicting the lifetime of geosynthetics. The material, its application and the environment for prediction are to be defined in detail. Data from site experience is given priority, if it is of sufficient quality. Accelerated testing can be performed by increasing the intensity (e.g. load, chemical concentration), the frequency or the temperature, provided that the principal mechanism of degradation remains unchanged. The predicted rate of degradation must state clearly which material the prediction is for and under which conditions. Where possible, samples should be included for future extraction to check whether the rate of degradation is as predicted.

1 INTRODUCTION

Many civil engineering structures are designed for long lifetimes, typically 100 years or more, and it is the desire of the design engineer that the materials that form the structure should function satisfactorily without replacement and with the minimum of maintenance. Established materials such as masonry and steel have been used for centuries and, with appropriate maintenance such as repainting, have proved durable over that time. Geosynthetics, however, have only been in existence for 40 years, and the plastics and polymer fibres from which they are made were invented in the mid 20th century. A durability of 100 years cannot therefore be demonstrated from experience alone.

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 certain level of durability can be assured. The "index" tests set out in Annex B to European Standards EN 13249-13257 and EN 13265 are believed to ensure a minimum durability of 25 years.

Not all applications require this level of lifetime. Some geotextiles are used in temporary works, or to provide a temporary function while the soil consolidates or vegetation grows. Highways structures, however, are designed typically for 100 years while in waste containment it is intended that the geosynthetic will last even longer.

With current knowledge it is not possible to define index tests for a durability for 100 years or more, since the necessary duration of some of these tests would be of too long for measurements to be made in advance of construction. Prediction of durability for such lifetimes has to be derived from a mixture of extrapolation from experience and accelerated testing. This paper is a summary of the approach we have presented in recent seminars and which will be the subject of a guideline issued within the European standards system. It also reflects the approach to the definition of reduction factors for soil reinforcement described in EN 20432.

2 DEGRADATION OF GEOSYNTHETICS

The manner in which geosynthetics degrade has been will described in the literature (CR ISO 13434, Brown & Greenwood 2000). It is important to differentiate between mechanisms that require a mechanical load, such as creep and environmental stress cracking, and those which proceed independently of load. While all geosynthetics will have been designed to minimise degradation, in some cases this will have been done by modifying the structure and in others by the inclusion of additives. In the second case the lifetime of the geosynthetic depends almost wholly on the choice and performance of the additives. The rates of degradation may be linear with time, or with log time, or neither; for example mechanical damage occurs principally at the start of a geosynthetic's life, while oxidation of a stabilised polypropylene can occur rapidly at the end of life once the antioxidant package has been consumed.

Assessment of the material in isolation is not sufficient to ensure durability. 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. High quality installation is of critical importance, particularly for geomembranes, and the loss of strength caused by damage during installation has to be taken into account for reinforcing geotextiles. Most failures that have occurred to date have been due to faulty design, incorrect choice of material, and poor or uncontrolled installation practices. Given satisfactory installation, however, the lifetime will depend on almost imperceptible changes that take place over time in the geosynthetic itself.

3 SYSTEM DEFINITION

Before embarking on an assessment the following must be defined:

- The material, including its chemical nature, any additives or coatings, and the physical structure of the geosynthetic: e.g. thick or thin fibres forming a woven or nonwoven fabric, extruded grid, coated fibrous strip, geosynthetic clay barrier, continuous sheet.
- The environment, including the particles, pH and saturation of the soil, the mechanical loads in all directions, any chemical contamination, the presence of light or of biological activity and, of course, the ambient temperature.
- The function, typically filtration, drainage, reinforcement, erosion control or containment.
- The design lifetime and whether any replacement or repair is acceptable.
- The end of life criterion, i.e. when the geosynthetic can no longer function satisfactorily. Examples of end of life are a 50% reduction in drainage cross-section or visible cracking in a geosynthetic barrier. For reinforcement applications the aim may be to define reduction factors based on the loss of strength of the geosynthetic.

4 EVIDENCE FROM SERVICE

Measurements of the degradation in real service environments are the most authoritative evidence for durability. Since geosynthetics have only been used for about forty years, 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. Inevitably, long-term experience generally refers to an earlier version of the product. Often the environment surrounding most geosynthetics is more benign than the extremes that were considered at the design stage. Many reports fall into the category of "nothing happened; nothing was expected to happen". Although such information is reassuring, measurement of actual change is necessary if the future rate of degradation is to be predicted.

Even when no experience is available, it is advisable to build it in for the future. Samples should be installed with the deliberate intention of extracting them at set intervals in order to monitor the degradation. It is essential that this work is correctly planned from the start, following the guidelines set down in ISO 13437. This includes the size and placement of samples and the method of extraction, repeatable procedures for measurement and the level of precision, the exclusion of light and elimination of the effect of mechanical damage, close monitoring of the environment, preservation of control material and the keeping of detailed records in a form that will be readable by our grandchildren.

5 ACCELERATED TESTING

5.1 *Increasing the frequency*

To satisfy the appetites of manufacturers and users hungry for immediate life predictions it is necessary to perform accelerated tests. Where the cause of degradation is intermittent, it may be possible to apply it with greater frequency. The rate of degradation due to light can in principle be doubled by illuminating the geotextile for 24 instead of 12 hours a day. For railway applications it may be possible drive wagons continuously. However, this approach cannot generally be applied to geosynthetics which are shielded from light and whose exposure to the environment is continuous.

5.2 *Increasing the severity*

In all accelerated testing it is necessary to identify the dominant mechanism of degradation: hydrolysis of a polyester in an alkaline environment, creep under mechanical load, oxidation of a polypropylene. In such cases the agent responsible for degradation – the pH, the load or the pressure of oxygen – can be increased. By performing tests under different conditions the rates of degradation at different intensities can be determined and thence the dependence of the rate of degradation (or time to failure) on intensity. For example, in creep-rupture testing a series of tests are performed on a reinforcing

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geotextile at high loads to enable a graph of load against time to failure (or more commonly log time) to be drawn. This can then be extrapolated from the short lifetimes measured at high loads to predict longer lifetimes at service loads (Fig. 1).

Sometimes it is not possible to increase the intensity without causing other effects, for example increasing the intensity of irradiation with light raises the temperature of the sample. Accelerated weathering tests form a separate discipline, but in spite of its complexity and the caveats of the operators, a reasonable level of correlation can be obtained by relating the extent of degradation to the radiant exposure, i.e. the accumulated dose of ultraviolet light. This is the basis for index test EN 12224.

5.3 *Increasing the temperature*

Temperature is very widely used to accelerate both chemical and physical processes. Extrapolation makes use of Arrhenius' formula,

$$A = A_0 \exp(-E/RT) \qquad (1)$$

where A is the rate of degradation, A_0 a constant, E the activation energy of the process in J/mol, R the universal gas constant (8.316 J/mol.K) and T is the absolute temperature in K (temperature in °C +273). 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 $-E/R$ (Fig. 2).

It is emphasised that Arrhenius' formula does not describe the rate of degradation, but only its dependence on temperature. Good planning of the tests is essential: maximum temperature is likely be limited by a transition such as the melting point and the minimum temperature by the predicted length of the test, while the temperature steps should be no greater than 10°C. When measurements are to be made at set time intervals, then these should be spaced logarithmically. Reserve specimens should be installed in case the durations have to be extended.

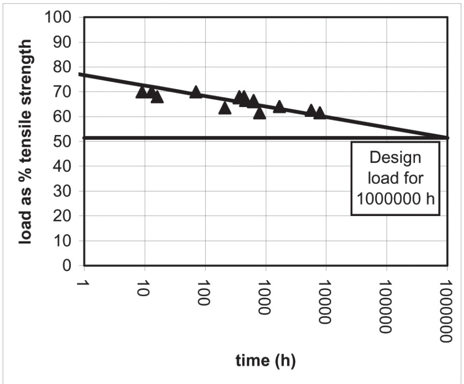

Figure 1. Creep-rupture diagram. The regression line derived from the measurements made at higher loads is extended to predict the design load for a 100 year lifetime.

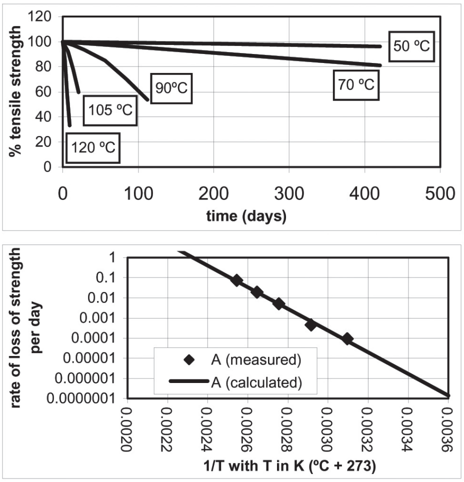

Figure 2. Arrhenius calculation. In the upper figure measurements of loss of strength are used to derive the rates of degradation A (gradients) at different temperatures T. In the lower diagram the rates are plotted against $1/T$ and extrapolated to give the proportional rate of loss of strength at 20°C (1/T = 0.0034) to be 0.0000014 /day (0.05 %/year).

It is not advisable to increase intensity and temperature simultaneously unless there is a clear understanding of the underlying mechanism. One example of where this is possible is the prediction of creep-rupture by means of Zhurkov's formula, a modification of Arrhenius' formula:

$$A = A_0 \cdot \exp[-(E-\sigma V)/RT] \qquad (2)$$

where A, A_0, E, R and T are as before, σ is the applied stress (or load) and V is a constant.

Creep strain measurements can be accelerated by time-temperature shifting, including the stepped isothermal method (ASTM D6992).

5.4 *Extrapolation*

Most data, whether from site monitoring or from accelerated testing, will require extrapolation in time to the duration of the service life. The key condition for this is that the mechanism of degradation must be unchanged over the full range of the accelerated tests and, as far as can be predicted, over the entire lifetime under service conditions. There should be no change in physical state of the material, for example glass transition, over the same range. Degradation of specimens from site or accelerated testing must look the same. There should be no development of, for example, surface cracking, unless the appearance of this cracking is taken as the end-of-life criterion. The degradation of a cracked material is likely to proceed faster due to progression of the cracks or the availability of oxygen.

Wherever possible extrapolation should use an established mathematical relation, such as Arrhenius' formula. If this is not available, the simplest explanation or formula that fits the measurements should be used (Occam 1320). 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.

Where two mechanisms take place sequentially, for example consumption of antioxidants followed by mechanical degradation of a polypropylene, then the two processes should be analysed separately and the predicted lifetimes added.

6 CONCLUSION: PREDICTION OF LIFETIME

The data from site, where available, and from accelerated testing, should then be assessed for the prediction of lifetime. Data from site should be adjusted to apply to the environment which a prediction is to be, using where appropriate Arrhenius' formulas for converting temperatures. Data on earlier products should be interpreted in the knowledge that products are generally changed in order to improve them, not the reverse. Data from site should be given priority over that from accelerated tests, unless the acceleration has identified a problem in the future that the site data has not yet had time to reveal. Data from index tests such as EN 12447 (hydrolysis) may be taken into account on the understanding that they represent extreme conditions. Generic data from the literature may also be taken into consideration.

The effects of mechanical damage during installation, whether correctly or incorrectly performed, should be identified so that they can be separated from long-term degradation. Failures at joints should not be taken as typical of the bulk material, however if joint failure is the end-of-life criterion then the prediction should be based on this alone. Any effects of weathering should also be separated from those due to chemical degradation.

The extent of extrapolation should be examined critically: particular care should be taken with logarithmic scales which condense long periods of real future time into conveniently short intervals on a diagram. Current practice is to extrapolate by durations of up to ten times without penalty. Further extrapolation should incur a precautionary factor (e.g. BS 8006:2001, Appendix A).

Confidence limits can be calculated in some cases, but statistical uncertainty should take into account the variability of the product as a whole, not just the results of a limited range of tests.

The statement of lifetime will follow the objectives first set out: for example a statement that the lifetime should exceed 100 years, or a reduction factor to be applied is design to take into account the changes that are predicted to take place. The statement should include:

- The material for which the prediction is made
- The end-of life criterion used.
- The principal degradation mechanism assumed.
- The environment to which the lifetime applies (e.g. temperature, saturation, pH).
- Any necessary maintenance or precautions.
- The level of confidence in the prediction.

Finally, the following general remarks:

- Correct installation is an essential precondition.
- It is only possible to predict what is known; no form of rational prediction can foresee problems for which there is as yet no evidence or scientific basis.
- Never forget how long 100 years really is - think back to the world of 1906.
- Ultimately you are the judge of what is a reasonable prediction, for example in the choice of a method of extrapolation.
- Experience to date has generally been good.

ACKNOWLEDGEMENTS

The authors thank the Directors of ERA Technology Ltd for permission to publish.

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