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The last word on reduction factors for soil reinforcement?

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ABSTRACT: We are approaching the stage where, for reinforcing geosynthetics based on polyester fibres, generic factors can be assigned to most of the design parameters for limit state design. This is subject to the materials meeting certain quality levels which can be assessed using short-term tests. Manufacturers can still, if they wish, specify individual partial factors for their products, based on specific tests. Individual partial factors will have to be defined for geosynthetics based on other polymers. For serviceability limit state design it is only necessary to define the allowable load with reference to the service temperature and the acceptable increase in post-construction strain.

1 SAFETY FACTORS

Design codes for reinforced soil include two principal safety factors. The first allows for uncertainty in the applied loads and for variability in the soil. The second applies to the reinforcement and allows for variability in its strength, for predicted long-term effects on that strength of sustained load, mechanical damage and the environment, and for uncertainty in those predictions. The design has to ensure that the risk of any failure is kept to a level commensurate with the consequences. This paper is concerned with the manner in which the second factor is calculated, and is restricted to polymer reinforcement.

2 PARTIAL SAFETY FACTORS

In all current design codes the safety factor is obtained by dividing the strength of the material by a number of partial factors, each reflecting one of the possible reasons for reduced strength. A review is given by Zornberg and Leshchinsky (2001). The resulting reduced strength will be described as the factored design strength.

In the British code BS 8006: 1995, which covers both steel and polymeric reinforcements, seven partial factors are specified, six of them relevant to polymers. These partial factors are as follows:

f_{m111} effectively replaces the mean tensile strength by the characteristic strength or the 90% (one-sided) lower confidence limit, calculated as the mean minus 1.64 x the standard deviation.

f_{m112} does not apply to polymers

f_{m121} is a factor which allows for a reduction in strength should the quality of the data used for determining the tensile strength be regarded as inadequate.

f_{m122} allows for uncertainty in the extrapolation between the creep strain or creep-rupture results and the design life. No factor is applied (i.e. $f_{m122} = 1.0$) if creep measurements have been made with a duration exceeding 10% of the design life. If the creep measurements extend to between 1% and 10% of the design life, f_{m122} increases with the logarithm of the ratio of design life to test duration, i.e. from 1.0 for 1 log cycle (the duration of the longest creep test equals 10% of the design life) to 2.0 for two log cycles (the duration of the longest creep test equals 1% of the design life).

f_{m211} allows for the reduction in strength of installation damage and is the ratio of the tensile strength of undamaged to material damaged as using the fill and compaction conditions expected on site.

f_{m212} allows for the additional long-term effects of installation damage.

f_{m22} allows for degradation due to environmental effects such as weathering during installation, chemical and possibly microbiological attack.

BS 8006 does not define how to derive the partial factors of safety. It does however provide for two alternative design strengths, T_{CS} and T_{CR}, the first to allow for serviceability or strain limit, the second to allow for ultimate limit state or rupture. Both require definition of a service lifetime. T_{CS} may be defined as the load at which the strain increase between the end of construction (a duration that itself requires definition) and the service lifetime equals the maximum permitted limit. This can be interpolated from the creep strain data. T_{CR} is calculated by extrapolating the creep-rupture line from measured data at higher loads and shorter times to lower loads and longer times until it intercepts the ordinate corresponding to the design lifetime. The corresponding load, defined as T_{CR}, is the sustained load which, if applied to the geosynthetic over the entire service lifetime, is predicted to lead to rupture on the last day of the design life.

The code published by the Association of American State Highway and Transportation Officials (AASHTO) (1997) bases its designs solely upon the tensile strength of the geosynthetic, defined as the minimum average roll value or MARV. This is set to be equal to two standard deviations below the mean, equivalent to the 97.5% (one-sided) lower confidence limit. The MARV strength is then divided by three factors:

$RF_{CR,}$ creep rupture, is the ratio of T_{CR} to the tensile strength of the batch on which the creep-rupture tests were carried, and the effect of applying RF_{CR} is to reduce the MARV strength in the same proportion. If the MARV strength divided by RF_{CR} is applied to the geosynthetic, then there should be a 2.5% chance that it will fail before or on the last day of the service life. Note that BS 8006 includes the effect of creep in the definition of strength, while the AASHTO code includes the effect of creep as a partial factor.

RF_{ID}, installation damage, is derived in the same manner as f_{m211} above.

RF_D, chemical resistance, is derived from predictions of the strength at the end of the design life. The predominant means of degradation in a polyester is by hydrolysis and that in a polyolefin (i.e. polypropylene or polyethylene) is by oxidation. More detailed instructions for how to derive the partial safety factors are given by Elias and Christopher (1997) and Elias (1997).

3 DEFAULT FACTORS

In common with other national codes, the AASHTO code allows default factors to be used for polyester and polyolefin based geosynthetics where no directly measured data are available. This is on the condition that the materials meet certain criteria which can be measured by relatively short-term tests. For the chemical degradation of polyesters these are a maximum carboxyl end group count and minimum averaged molecular weight, for polyolefins a minimum retained strength following a weathering test for polyolefins. The default factors are substantial, 3.5 for temporary structures and 7.0 for permanent structures, making it attractive to measure data on the geosynthetic itself.

4 RECENT DEVELOPMENTS

Recent developments suggest that the time is coming to simplify this situation, namely:

- The strains within monitored reinforced soil structures are generally much less than those predicted in design.
- Experience is proving that limit strain (serviceability) is more likely to be the design criterion than is creep-rupture.
- Stepped Isothermal Method (SIM) tests indicate that the long-term effect of installation damage is no greater than is predicted from short term tests (J H Greenwood, unpublished results).
- Residual strength tests indicate that the tensile strength of a geosynthetic remains practically unchanged until just before rupture.
- Understanding of hydrolytic and oxidative processes in polymers is improving.
- Most reported failures of earthworks and structures containing geosynthetic reinforcements are due to errors in design and poor construction practice, and not to a loss of durability of the reinforcement.
- The development of quality assurance schemes to ensure that a manufacturer's product has the properties advertised.
- A large amount of data on the creep-rupture of polyesters shows that their creep-rupture behaviour lies within fairly predictable confidence limits.

The consequences of these findings will now be discussed.

The reason for the low strains observed on reinforced structures is because the soil/reinforcement interaction provides a higher strength capability than is allowed for (see for example Rowe and Li 2001). This suggests that, even allowing for some contingency, the overall factor of safety for the structural design could be reduced. This does not affect the partial factors for the geosynthetic, but could lead to a lower overall safety factor for the structure.

For many structures it will be the serviceability limit that will define the design load. Most of the effects described have little effect on the strain behaviour (i.e. equal 1.0 when applied to T_{CS}) but reduce the strength substantially (i.e. > 1.0 when applied to T_{CR}). It is therefore essential to define the partial factors separately in each case. Variations in temperature are likely to be the most significant effect on modulus.

Long-term creep tests on damaged and undamaged samples of the same uncoated polyester geosynthetic using the SIM indicate that the design strength based on the creep-rupture of damaged material is equal to or slightly greater than that given by the allowable load divided by ($RF_{CR} \times RF_{ID}$), with RF_{CR} derived from creep-rupture tests on undamaged material and RF_{ID} based on short-term tensile tests. The consequence of this is that f_{m212} can be set equal to 1.0.

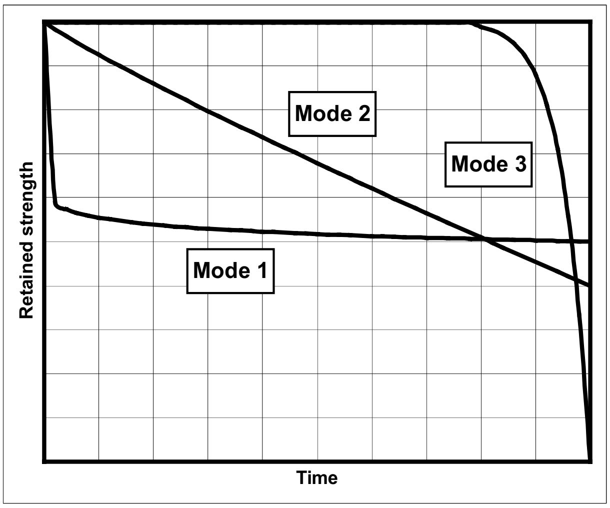

Figure 1 Illustration of three modes of degradation: In mode 1 all the degradation takes place at the start, in mode 2 progressively, and in mode 3 at the end of life.

An extensive programme of residual strength tests has demonstrated that the residual strength of both polyester and polyethylene reinforcing geosynthetics is retained up to the time span where there is a significant probability of creep-rupture. This implies that the mechanism of creep-rupture is a catastrophic phenomenon which shows little sign of its development until the conditions for rupture develop, such as the rupture of a few percent of the fibres. Because of the statistical risk this has little influence on the design where this is dictated by creep-rupture, but it is of great importance when a reserve of strength has to be maintained, above all for seismic design. This is the subject of a separate paper at this conference (Greenwood, Jones and Glendinning 2002).

This relatively rapid form of rupture is typical not only of residual strength but also of other forms of degradation. One example is oxidation, which becomes effective only when all the antioxidant stabiliser package has been consumed, leaving the polymer unprotected. More generally, degradation mechanisms can be grouped into three modes (Fig. 1). In mode 1 all the degradation takes place at the start, in mode 2 progressively, and in mode 3 at the end of life. It is clear that the reduction factor for mode 1 should take immediate effect and be independent of time. An example is RF_{ID}. The reduction factor corresponding to mode 2 will be time-dependent, for example the progressive reduction in strength predicted for hydrolysis. For mode 3, however, a reduction factor applied to load is inappropriate. It is instead essential to predict the time to failure, together with its variability. Any partial factor should then be applied to time and not load. This approach will be explored further below.

Tests on oxidation and hydrolysis have confirmed that hydrolysis is a progressive effect which initially causes some splitting of the polymer chain, resulting in a decrease in molecular weight and an increase in carboxyl end groups, and leading only later to a significant reduction in strength. However, tests to date have lasted for a year at most, allowing considerable scope in the manner in which they are extrapolated and a corresponding variability in RF_D. Oxidation is an altogether more complex process whose development depends on the ratio of surface to volume and effects such as the surface micro-cracking of certain materials that promotes further oxidation. It has proved impossible to date to devise a single test to predict or act as a screening test for the oxidation resistance of a geosynthetic.

The lack of any failures in soil structures due to poor durability should not be a cause for complacency. In industrial products it is well known that a high frequency of initial failures is followed by a period where failure is rare, until towards the end of the service life when the rate of failure rises again. Those early failures are due to problems with production and assembly; the later ones due to durability and wear-out. So it is with soil structures: so far we have seen the failures due to faulty design or faulty installation, and we hope that there will be a long and uneventful period before the true effects of durability begin to show themselves.

The effect of the quality assurance schemes is to provide more confidence in the strengths stated by manufacturers such that there can be less insistence on independent testing. The design engineer will not know whether his structure will be constructed with a roll of material that is above or below average strength, but he should have increasing confidence that the nominal strength will be achieved. In the absence of any independent quality assured strength the designer should be able to base his design on the manufacturer's stated value; the manufacturer's own quality assurance will define that this value is met within preset confidence limits.

Most commercially available polyester geosynthetics are manufactured from a limited number of commercially available fibres with molecular weights and carboxyl end group counts within the limits set by AASHTO. It is therefore unsurprising that the values of RF_{CR} derived from creep-rupture tests, augmented for some products by tests at higher temperatures to improve confidence in extrapolation by time-temperature superposition or by SIM tests, lie within a relatively narrow band. It would therefore be appropriate to allow a default factor of RF_{CR} = 1.25 for t = 1 h rising to 2.0 for t = 10^6 h or 114 years, above which all currently commercially available polyester reinforcements lie. In the same way it should be possible to define a maximum value for the post-construction creep strain, taken for example as the strain measured in air between 100 h and a design life of 10^6 h (114 years). The strain on loading, which is notoriously variable and appears to depend on the structure of the material as well as on the exact loading procedure, is then excluded.

5 A SIMPLIFIED PROCEDURE

We are approaching a situation in which the following simplified procedure could be considered:

For serviceability (limit state) design with polyester reinforcement there will be a default relation between tensile strength, construction time, service life, service temperature and maximum allowable load. For other materials the allowable load should be based on creep testing. If a manufacturer wished to recommend use of higher design load these would have to be based on creep testing. No further reduction factor is required.

For ultimate limit state design (rupture) the basic strength should be that stated by the manufacturer: his quality assurance system will ensure that material with this strength is provided. This strength is reduced by three reduction factors and a safety factor: the AASHTO notation is used in view of its simplicity.

RF_{CR} for creep-rupture of a polyester can be defined by a generic value, unless the manufacturer chooses to provide an alternative value based on measurements on his product. RF_{CR} does not apply to seismic design using residual strength.

RF_{ID} is defined by tensile tests on damaged material.

RF_D is defined as a fixed value, for example 1.2, for a stated design life under stated conditions.

The safety factor FS collects all the effects of variability and uncertainty.

6 THE CONDITIONS

The increasing use of default factors for polyesters reflects the similarity in the performance of commercially available products. To eliminate the use of less durable grades, however, certain short-term screening tests must be introduced. This follows the same pattern as AASHTO, but in view of the increasing body of information the default factors can afford to be less extreme. For plastic pipes, where there are several decades of experience with time to rupture under pressure, proof tests are used to ensure that a batch of pipe conforms to the general creep-rupture pattern for the polymer from which it is made. For polyester geosynthetics SIM would be ideal to perform a limited number of creep-rupture tests to confirm that the lifetime of the geosynthetic under load exceeds a certain minimum duration. To avoid allowances for uncertainty being included more than once, it is important that the default factors become generic or typical rather than maximum, and that all the allowances for uncertainty and extrapolation are transferred to an overall safety factor FS.

Geogrids made from polyethylene and other polymers would require individual testing.

The effect of installation damage can substantial. In the interest of both safety and economy it is important that an accurate assessment of this factor is made. Full scale damage tests as described by Watts and Brady (1990) are performed on specimens typically 2 m square, making it a test that is representative but expensive where only small quantities are required. ENV10722-1, in which a conventional wide width tensile specimen is placed in 0.3 m square box containing an alumina aggregate and then subjected to dynamic compression, has been shown to rank materials correctly and to give results that are representative of the aggregate granularity. The correlation with site conditions is however not good enough for it to be used alone. Default factors have been suggested for a range of fills and geosynthetics but require further validation for them to be applied generally (Elias 1997). Again, these should become generic and not maximum factors.

The effect of weathering on site would be taken into account by restricting the time during which a geosynthetic can be left exposed during installation, in the same manner as in EN 13251, Annex B.

For chemical degradation the method would be to define a lifetime rather than a partial factor, subject to screening tests on the material. This system is already partly in place in the AASHTO and European systems. AASHTO sets minimum requirements on the material if default factors are to be used. EN 13251 requires testing to EN 12447 if a polyester is to last for 25 years. These need extension to longer assured times and less conservative default factors.

The overall factor of safety FS allows for variability and the uncertainty of extrapolation. It is important to separate prediction from uncertainty, since if several partial factors are combined, each of which has been set at a high level to allow for variability or uncertainty of extrapolation, the final product will be unrealistically conservative.

7 CONCLUSION

We can aim towards a system where, for reinforcing geosynthetics based on polyester fibres, generic factors can be assigned to most of the design parameters for limit state design. Installation damage will require measurement for the present, and for this a less elaborate method is required. The system still allows a manufacturer to specify individual partial factors for his product, based on specific tests. Individual partial factors would have to be defined for geosynthetics based on other polymers. For serviceability design only the allowable load requires definition with reference to the service temperature.

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