

WSDOT Standard Practice T 925

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WSDOT Standard Practice T 925

Standard Practice for Determination of Long-Term Strength for Geosynthetic Reinforcement

Summary and Use of Standard Practice

Through this protocol, the long-term strength of geosynthetic reinforcements can be determined. This protocol contains test and evaluation procedures to determine reduction factors for installation damage, creep, and chemical/biological durability, as well as the method to combine these factors to determine the long-term strength. The long-term strength values determined from this protocol can be compared to the required design strengths provided in the contract for the geosynthetic structure(s) in question to determine if the selected product meets the contract requirements. This protocol can be used for initial product qualification or acceptance (e.g., for inclusion in the Qualified Products List), or for quality assurance (QA) to facilitate periodic review of products for which the long-term strength has been previously determined using this Standard Practice.

This protocol has been developed to address polypropylene (PP), polyethylene (PE or HDPE), and polyester (PET) geosynthetics. For other geosynthetic polymers (e.g., polyamide or PVA), the installation damage and creep protocols provided herein are directly applicable. While the chemical and biological durability procedures and criteria provided herein may also be applicable to other polymers (for example, hydrolysis testing as described in Appendix D is likely applicable to polyamide and PVA geosynthetics), additional investigation will be required to establish a detailed protocol and acceptance criteria for these other polymers. These other polymers may be considered for evaluation using this protocol once modifications to the chemical/biological durability aspects of this protocol have been developed and are agreed upon by the approval authority.

Abbreviations and Symbols

AASHTO = American Association of State Highway and Transportation Officials

d₅₀ = The grain size at 50% passing by weight for the backfill.

HDPE = High Density Polyethylene

MARV = The minimum average roll value for the geosynthetic, defined as two standard deviations below the mean for the product (i.e., 97.5% of all test results will meet or exceed the MARV). For practical purposes from the user's viewpoint, the average for a sample taken from any roll in the lot shipped to the job site should meet or exceed the MARV.

MSE = Mechanically Stabilized Earth

PET = Polyester

PP	=	Polypropylene
QPL	=	Qualified Products List
RF	=	Combined reduction factor to account for long-term degradation due to installation damage, creep, and chemical/biological aging
RF_{CR}	=	Strength reduction factor to prevent long-term creep rupture of the reinforcement
RF_D	=	Strength reduction factor to prevent rupture of the reinforcement due to long-term chemical and biological degradation
RF_{ID}	=	Strength reduction factor to account for installation damage to the reinforcement
T_{al}	=	The long-term tensile strength which will not result in rupture of the reinforcement during the required design life, calculated on a load per unit of reinforcement width basis
T_{ult}	=	The ultimate tensile strength of the reinforcement determined from wide width tensile tests
UV	=	Ultraviolet light
WSDOT	=	Washington State Department of Transportation

Definitions

<i>Apertures</i>	The open spaces formed between the interconnected network of longitudinal and transverse ribs of a geogrid.
<i>Class 1 Structure</i>	Typically includes geosynthetic walls or slopes that support bridge abutments, buildings, critical utilities, or other facilities for which the consequences of poor performance or failure would be severe. In general, geosynthetic walls greater than 6 m (20 ft) in height and reinforced slopes greater than 9.2 m (30 ft) in height will be considered to be Class 1.
<i>Class 2 Structure</i>	All geosynthetic walls and slopes not considered to be Class 1.
<i>Confined Testing</i>	Geosynthetic testing in which the specimen is surrounded and confined by soil to simulate conditions anticipated for the geosynthetic in use.
<i>Effective Design Temperature</i>	The temperature that is halfway between the average yearly air temperature and the normal daily air temperature for the warmest month at the wall site.
<i>Hydrolysis</i>	The reaction of water molecules with the polymer material, resulting in polymer chain scission, reduced molecular weight, and strength loss.
<i>In-isolation Testing</i>	Geosynthetic testing in which the specimen is surrounded by air or a fluid (not soil).
<i>Installation Damage</i>	Damage to the geosynthetic such as cuts, holes (geotextiles only), abrasion, fraying, etc., created during installation of the geosynthetic in the backfill soil.

<i>Load Level</i>	For creep or creep rupture testing, the load applied to the test specimen divided by T_{lot} , the short-term ultimate strength of the lot or roll of material used form the creep testing.
<i>Nonaggressive Environment</i>	For geosynthetic walls and slopes, soils which have a d_{50} of 4.75 mm or less, a maximum particle size of 31.5 mm or less, a pH of 4.5 to 9, and an effective design temperature of 30° C or less.
<i>Oxidation</i>	The reaction of oxygen with the polymer material, initiated by heat, UV radiation, and possibly other agents, resulting in chain scission and strength loss.
<i>Post-consumer Recycled Material</i>	Polymer products sold to consumers which have been returned by the consumer after use of the products for the purpose of recycling.
<i>Product Line</i>	A 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 weight/unit area or number of fibers contained in each reinforcement element.
<i>Sample</i>	A portion of material which is taken for testing or for record purposes, from which a group of specimens can be obtained to provide information that can be used for making statistical inferences about the population(s) from which the specimens are drawn.
<i>Specimen</i>	A specific portion of a material or laboratory sample upon which a test is performed or which is taken for that purpose.
<i>Survivability</i>	The ability of a geosynthetic to survive a given set of installation conditions with an acceptable level of damage.

Test Methods and Practices Used

The following test methods and practices are used or referenced by Standard Practice T 925:

1. AASHTO Bridge Standard Specifications for Highway Bridges, 17th Edition, 2002
2. AASHTO Bridge LRFD Specifications for Highway Bridges, 3rd Edition, 2004 with current interims
3. ASTM D4354 Standard Practice for Sampling of Geosynthetics for Testing
4. ASTM D4873 –Standard Guide for Identification, Storage, and Handling of Geosynthetic Rolls and Samples
5. ASTM D5261 – Standard Test method for Measuring Mass per Unit Area of Geotextiles
6. ASTM D4595 – Standard Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method
7. ASTM D 6637 – Standard Test Method for Determining Tensile Properties of Geogrids by the Single or Multi-Rib Tensile Method.

8. ASTM D-1248 – Standard Specification for Polyethylene Plastics Extrusion Materials for Wire and Cable
9. ASTM D-4101 – Standard Specification for Polypropylene Injection and Extrusion Materials
10. WSDOT Test Method T 926 – Geogrid Brittleness Test
11. ISO/DIS 10722-1 - Procedure for simulating damage during installation. Part 1: Installation in granular materials
12. ASTM D5818 – Standard Practice for Obtaining Samples of Geosynthetics from a Test Section for Assessment of Installation Damage
13. ASTM D2488 – Standard Practice for Description and Identification of Soils (Visual-Manual Procedure)
14. ASTM D1557 – Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft³)(2700 kN-m/m³)
15. AASHTO T96 - Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
16. ASTM D6992 – Accelerated Tensile Creep and Creep-Rupture of Geosynthetic Materials Based on Time-Temperature Superposition Using the Stepped Isothermal Method
17. ASTM D5262 – Standard Test Method for Evaluating Unconfined Tension Creep Behavior of Geosynthetics
18. ISO/FDIS 9080:2001 - Plastic piping and ducting systems – Determination of long-term hydrostatic strength of thermoplastics materials in pipe form by extrapolation.
19. ASTM D2837 – Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials
20. ASTM D4355 – Standard Test Method for Deterioration of Geotextiles from Exposure to Ultraviolet Light and Water (Xenon-Arc Type Apparatus)
21. ASTM D4603 – Standard Test Method for Determining Inherent Viscosity of Poly(Ethylene Terephthalate) (PET) by Glass Capillary Viscometer
22. GRI-GG7 – Carboxyl End Group Content of PET Yarns
23. GRI-GG8 – Determination of the Number Average Molecular Weight of PET Yarns Based on a Relative Viscosity Value
24. ASTM D3045 – Standard Practice for Heat Aging of Plastics Without Load
25. ASTM D 3417-99 - Enthalpies of Fusion and Crystallinization of Polymers by DSC
26. ENV ISO 13438:1999 - Geotextiles and Geotextile-Related Products - Screening Test Method for Determining the Resistance to Oxidation
27. ASTM D 3895 – Standard Test Method for Oxidative-Induction Time of Polyolefins by Differential Scanning Calorimetry
28. ASTM D 5885 – Standard Test Method for Oxidative Induction Time of Polyolefins by High-Pressure Differential Scanning Calorimetry

Per mutual agreement between the testing laboratory, the geosynthetic manufacturer, and the approval authority, "equivalent" ISO standards and practices may be used in lieu of ASTM, AASHTO, or GRI standards and practices where equivalent procedures are available.

Data Requirements for Initial Product Acceptance

1. General Product Information (required for all geosynthetic reinforcement products):
 - a. Geosynthetic type and structure.
 - b. Spacing and dimensions of geogrid elements. The receiving laboratory should verify these dimensions upon receipt of the sample(s) using hand measurement techniques. This is especially critical for strength determination based on a single or limited number of ribs in the specimens tested.
 - c. Polymer(s) used for fibers, ribs, etc.
 - d. Polymer(s) used for coating, if present.
 - e. Roll size (length, width, and area).
 - f. Typical lot size.
 - g. Polymer source(s) used for product.
 - h. For HDPE and PP, primary resin ASTM type, class, grade, and category (for HDPE use ASTM D-1248, and for PP use ASTM D-4101).
 - i. For PET, minimum production number average molecular weight (ASTM D4603 and GRI:GG8) and maximum carboxyl end group content (GRI:GG7), with supporting test data. Information regarding the laboratory where the testing was conducted and date of testing shall also be provided.
 - j. % of post-consumer recycled material by weight.
 - k. Minimum weight per unit area for product (ASTM D5261).
 - l. MARV for ultimate wide width tensile strength (ASTM D4595 or ASTM D6637), with supporting test data. Information regarding the laboratory where the testing was conducted and date of testing shall also be provided.
 - n. UV resistance at 500 hours in weatherometer (ASTM D4355), with supporting test data (as a minimum, provide supporting data for one product in the product line, preferably the lightest weight product submitted in the product line). Information regarding the laboratory where the testing was conducted and date of testing shall also be provided.
 - o. In addition, to establish a baseline for quality assurance testing, oven aging tests conducted in accordance with ENV ISO 13438:1999, Method A (PP) or B (HDPE), for polyolefin geosynthetics shall be performed. As a minimum, the lightest weight product in the product line should be tested. Unexposed and post-exposure specimens shall be tested for tensile properties (ASTM D4595 or ASTM D6637).
 - p. for geogrids, evaluation of geogrid brittleness per WSDOT Test Method T 926.

2. Installation Damage Data Requirements (RF_{ID}):

Installation damage testing and interpretation shall be conducted in accordance with Appendix A. As a minimum, for each product tested, the following information should be obtained:

- a. Date tests were conducted.
- b. Name(s), location(s), and telephone number(s) of laboratory(ies) conducting the testing and evaluation.
- c. Identify whether installation damage testing was conducted as a site specific evaluation for an actual construction project or was conducted as a non-site specific evaluation.
- d. Description of specific procedures used to conduct the installation damage testing, including installation procedures, sample size, method of specimen selection, sample removal procedures, etc. Identify any deviations in the installation procedures relative to typical installation practice in full scale structures, if the testing was not site specific.
- e. Photographs illustrating procedures used and the conditions at the time of the testing, if available.
- f. Measured mass/unit area per ASTM D5261 for the sample tested for installation damage and for the sample used to establish the undamaged strength. Also obtain product manufacturer Quality Control (QC) data on the uncoated product (i.e., “greige -good”) for the lot used for installation damage testing.
- g. Tensile test results for the product before exposure to installation conditions (i.e., virgin material), and whether both virgin and damaged samples were taken from the same roll of material, or just from rolls within the same lot of material.
- h. Tensile test results for specimens taken from the damaged material after installation.
- i. Tensile test results for both virgin and damaged specimens should include individual test results for each specimen, typical individual load-strain curves which are representative of the specimens tested, including associated calibration data as necessary to interpret the curves (curves in which strain and load/unit width are already calculated are preferred), the average value for each sample, the coefficient of variation for each sample, and a description of any deviations from the standard tensile test procedures required by Appendix A.
- j. Gradation curves for backfill material located above and below the installation damage geosynthetic samples, including the d_{50} size, maximum particle size, and a description of the angularity of the soil particles per ASTM D2488, including photographs illustrating the soil particle angularity, if available. Also include LA Wear test results for the backfill material used.
- k. Photographs and/or a description of the type and extent of damage visually evident in the exhumed samples and specimens.
- l. RFID, and a description of the data interpretation method used to determine RF_{ID} for each sample.

3. Creep Data Requirements (RF_{CR} and Creep Stiffness J):

Creep testing and interpretation shall be conducted in accordance with Appendices B and C. As a minimum, for each product tested, the following information should be obtained:

- a. Date tests were conducted.
- b. Name(s), location(s), and telephone number(s) of laboratory(ies) conducting the testing and evaluation.
- c. Photographs illustrating the creep testing equipment and procedures used, as available.
- d. Tensile test results for the product before creep testing (i.e., virgin material), and whether both virgin and creep tested samples were taken from the same roll of material, or just from rolls within the same lot of material.
- e. Tensile test results should include individual test results for each specimen, typical load-strain curves which are representative of the specimens tested, including associated calibration data as necessary to interpret the curves (curves in which strain and load/unit width are already calculated are preferred), the average value for each sample, the coefficient of variation for each sample, and a description of any deviations from the standard tensile test procedures required by Appendices B and C.
- f. Creep test procedures used, especially any deviations from the procedures required in Appendices B and C.
- g. If RF_{CR} is determined using data obtained in accordance with Appendix B, provide load and time to rupture for each specimen as a minimum; however, strain data as a function of time are desirable if available.
- h. If RF_{CR} is determined using data obtained in accordance with Appendix C, provide strain data as a function of time, and strain at beginning of tertiary creep (if rupture occurred), in addition to load applied and time to rupture (if rupture occurred), is required.
- j. Creep data plots should include both major and minor gridlines for ease in viewing and interpreting the data.
- k. If elevated temperature testing is conducted, creep data before and after time/load shifting, including shift factors used and a description of how the shift factors were derived, must be provided.
- l. Data illustrating the variability of the creep test environment, including temperature and humidity, during the creep test time period, or some assurance that the creep test environment was maintained within the variation of temperature prescribed within Standard Practice T 925, must be provided.
- m. A detailed description of creep extrapolation procedures used (i.e., step-by-step procedures and theoretical/empirical justification) if procedures other than those outlined in Appendices B and C are used.

- n. Description of statistical extrapolation procedures used in accordance with Appendices B and C, if statistical extrapolation is performed.
 - o. RFCR, and a description of how RF_{CR} was determined for each product.
 - p. In addition, regardless of which approach is used to determine RF_{CR} , creep strain data at a load level that results in a strain of 2% at approximately 1,000 hours shall be submitted to determine the low strain (i.e., 2%) creep stiffness at 1,000 hours and at the specified design life (typically 75 years) using isochronous curves determined in accordance with Appendix C.
 - q. For both creep rupture and low strain creep stiffness testing, if single rib, yarn, or narrow width specimens are used, 1,000 hour creep data in accordance with Appendices B and C that demonstrates the single rib, yarn, or narrow width test results are consistent with the results from multi-rib/wide width testing.
4. Long-Term Durability Data Requirements (RF_D):

As a minimum, the durability test data requested in part (1), which include molecular weight and CEG for PET, oven aging tests for polyolefins, and UV resistance for all polymers, shall be provided.

If it is desired to submit detailed durability performance test data to justify a lower RF_D , or to allow use in environments classified as chemically aggressive, durability testing and interpretation shall be conducted in accordance with Appendix D, and, as a minimum, for each product tested, the following information should be obtained:

- a. Date tests were conducted.
- b. Name(s), location(s), and telephone number(s) of laboratory(ies) conducting the testing and evaluation.
- c. Photographs and drawings illustrating the durability testing equipment and procedures used, as well as a summary of the specific procedures used.
- d. Tensile test results for the product before durability testing (i.e., virgin material), and whether both virgin and durability test samples were taken from the same roll of material, or just from rolls within the same lot of material.
- e. Polymer characteristics for the lot or roll of material actually tested before long-term exposure in the laboratory, including, for example, molecular weight and carboxyl end group content for PET, melt flow index and OIT for polyolefins, percent crystallinity, SEM photographs of fiber surface, etc.

Note 1: Percent crystallinity can be determined using Differential Scanning calorimetry (DSC). An appropriate test method is ASTM D3417-99. By definition, crystallinity (X) is calculated as follows:

$$X = \frac{\Delta H}{\Delta H^\circ} \text{ (times 100 for %)}$$

where:

ΔH is the latent heat under the DSC melt curve

ΔH° is the latent heat for a 100% crystalline polymer

Temperature scan should start 10° C below, continue through, and stop 10° C above the melt range. Recommended test parameters are as follows:

Homo-Polymer	Sample Size (mg)	Melt Range (°C)	Latent Heat, ΔH° (cal/gm)	DSC Scan Speed (°C/min)
HDPE	5	100-145	68.4	10
PP	7.5	100-165	45	10
PET	10	200-245	30	10

Other values of sample size, melt range, and DSC scan speed can be used with justification.

- f. Tensile test results for specimens taken for each retrieval from the incubation chambers.
 - g. Tensile test results, including tensile strength, strain at peak load, and 5 percent secant or offset modulus, for both virgin material and degraded material should include individual test results for each specimen, typical load-strain curves which are representative of the specimens tested, including associated calibration data as necessary to interpret the curves (curves in which strain and load/unit width are already calculated are preferred), the average value for each sample, the coefficient of variation for each sample, and a description of any deviations from the standard tensile test procedures required by Appendix D.
 - h. A detailed description of the data characterization and extrapolation procedures used, including data plots illustrating these procedures and their theoretical basis.
 - i. Results of any chemical tests taken (e.g., OIT or HPOIT, molecular weight, product weight/unit area, etc.), and any scanning electron micrographs taken, to verify the significance of any degradation in strength observed.
 - j. Results of biological degradation testing, if performed.
 - k. RFD, and a description of the method used to determine RF_D for the product.
5. Evaluation of Product Lines

If determining the long-term strengths for a product line, the data required under “General Product Information” must be obtained for each product. Product specific information for creep and durability must be obtained for at least one product in the product line to qualify the product line for Class 1 structures or aggressive environments, or in the case of Class 2 structures to allow the use of a total long-term strength reduction factor of less than 7 (see description of environment aggressiveness and Class 1 and Class 2 structures in “Determination Of Long-Term Geosynthetic Strength” later in this Standard Practice). Additional product specific information for creep and durability shall also be obtained for each product in the product line in accordance with Appendices B, C and D regarding use of long-term data for “similar” products. This data is to be used to determine long-term strengths for each product in the product line.

In general, product specific installation damage data must be obtained for each product in the line. However, it is permissible to obtain installation damage data for only some of the products in the product line if interpolation of the installation damage reduction factor between products is feasible. Interpolation of the product specific installation damage reduction factor RF_{ID} between tested products can be based on the weight per unit area or undamaged tensile strength of each product, provided that the progression of weight per unit area or tensile strength as compared to the progression of RF_{ID} for each tested product is consistent. For coated geogrids, the weight of coating placed on the fibers or yarns may influence the amount of installation damage obtained (Sprague, et al., 1999). In that case, the installation damage reduction factor may need to be correlated to the coating weight instead. If it is determined that the RF_{ID} values obtained for a product line are not correlated with product weight per unit area, undamaged tensile strength, coating weight, or some other product parameter, and the variance of RF_{ID} between any two products in the product line is 0.1 or more, then each product in the product line shall be tested.

Determination of Long-term Geosynthetic Strength for Initial Product Acceptance

1. Calculation of Long-Term Strength

Reinforcement elements in MSE walls and reinforced slopes should be designed to have a durability to ensure a minimum design life of 75 years for permanent structures in accordance with AASHTO (2002, 2004). For ultimate limit state conditions:

$$T_{al} = \frac{T_{ult}}{RF} \quad (1)$$

where:

$$RF = RF_{ID} \times RF_{CR} \times RF_D \quad (2)$$

T_{al} = The long-term tensile strength that will not result in rupture of the reinforcement during the required design life, calculated on a load per unit of reinforcement width basis

T_{ult} = the ultimate tensile strength (MARV) of the reinforcement determined from wide width tensile tests

RF = a combined reduction factor to account for potential long-term degradation due to installation damage, creep, and chemical/biological aging

RF_{ID} = a strength reduction factor to account for installation damage to the reinforcement

RF_{CR} = a strength reduction factor to prevent long-term creep rupture of the reinforcement

RF_D = a strength reduction factor to prevent rupture of the reinforcement due to chemical and biological degradation

See Appendices A through D for protocols to use to determine RF from product specific data. Unless otherwise indicated in the contract specifications for a given project, the design temperature used to determine RF and T_{al} from product specific data shall be assumed to be 20° C (68° F).

The value selected for T_{ult} is the minimum average roll value (MARV) for the product to account for statistical variance in the material strength. T_{ult} should be based on a wide width tensile strength (i.e., ASTM D4595 for geotextiles or ASTM D6637 for geogrids). Other sources of uncertainty and variability in the long-term strength include installation damage (Appendix A), creep extrapolation (Appendices B and C), and chemical degradation (Appendix D). It is assumed that the observed variability in the creep rupture envelope is 100% correlated with the short-term tensile strength, as the creep strength is typically directly proportional to the short-term tensile strength within a product line (see Appendix B and Note 7 in Appendix B if this is not the case). Therefore, the MARV of T_{ult} adequately takes into account that source of variability. For additional discussion of this issue, see Note 2 below.

Note 2: *The product strength variability is not taken into account by using the creep limited strength, T_l , directly or in normalizing T_l by T_{lot} (see Appendix B). T_l only accounts for extrapolation uncertainty. Furthermore, T_{lot} is specific to the lot of material used for the creep testing. Normalizing by T_{lot} makes the creep reduction factor RF_{CR} applicable to the rest of the product line, as creep strength is typically directly proportional to the ultimate tensile strength, within a product line.. As shown below, it is not correct to normalize the creep strength T_l using T_{ult} , the MARV of the tensile strength for the product, nor is it correct to use T_l directly in the numerator to calculate T_{al}*

$$RF_{CR} = \frac{T_{lot}}{T_l} \neq \frac{T_{ult}}{T_l} \quad \text{and} \quad T_{al} \neq \frac{T_l}{RF_{ID} \times RF_D}$$

In the former case, the creep strength is not indexed to the actual tensile strength of the material used in the creep testing, and since there is a 50% chance that T_{ult} will be less than or equal to T_{lot} , using T_{ult} in this case would result in an unconservative determination of RF_{CR} . In the latter case, where T_l is used directly as a creep reduced strength, the product strength variability is not taken into account, since T_l is really a mean creep strength. Hence, RF_{CR} must be determined as shown in Equation B.4-1 (see Appendix B), and the MARV must be used for T_{ult} when determining T_{al} . Note that the use of the MARV for T_{ult} may not fully take into account the additional variability caused by installation damage. For the typical degree of installation damage observed in practice, this additional variability is minor and can be easily handled through the overall safety factor used in design of reinforced structures. For durability (RF_D), additional variability does not come into play if a default reduction factor is used. If a more refined durability analysis is performed, additional variability resulting from chemical degradation may need to be considered.

The type and amount of data to be obtained, and the approach used to determine the long-term design strength, will depend on the geosynthetic wall or reinforced slope class and the aggressiveness of the environment.

2. Wall or Slope Class

The class of a given geosynthetic structure will be identified in the contract specifications. A Class 1 geosynthetic wall or reinforced slope typically includes walls or slopes that support bridge abutments, buildings, critical utilities, or other facilities for which the consequences of poor performance or failure would be severe. Examples of severe consequences include serious personal injury, loss of life, or significant property damage. Cost and impact to the public if a poorly performing wall or slope must be repaired or replaced may also be considered in the determination of wall or slope class. In general, geosynthetic walls greater than 6 m (20 ft) in height and reinforced slopes greater than 9.2 m (30 ft) in height will be considered to be Class 1. All other geosynthetic walls and reinforced slopes will in general be considered to be Class 2. The specific application of geosynthetic structure class shall be carried out in accordance with AASHTO (2002, 2004) and other requirements of the approval authority.

3. Environment Aggressiveness

A nonaggressive environment is defined based on soil gradation and particle characteristics, chemical properties of the environment, and site temperature. Normally, the backfill pH will be the key chemical property that will affect the chemical aggressiveness of the geosynthetic environment. Soil gradation and particle characteristics primarily affect potential high RF_{ID} values, chemical properties affect the potential for high RF_D values, and temperature affects potential for high RF_D and high RF_{CR} values. The aggressiveness of the soil gradation will depend on the distribution, the maximum size, the angularity, and the durability of the soil particles. In general, the more angular the soil, the more uniform its gradation, the greater the maximum particle size, and the more durable the particles, the more aggressive the soil is with regard to potential for installation damage. Installation damage for geosynthetic reinforcement has been approximately correlated to the d_{50} size of the soil, and the d_{50} size can be used as a basis to interpolate to a specific soil gradation using test results at other gradations (Elias, 2000). However, other gradation characteristics may need to be considered to more accurately interpolate to a specific soil gradation and angularity. While installation damage can be evaluated for the anticipated soil gradation and characteristics, it is generally undesirable to use soils and associated installation conditions that result in a RF_{ID} value that is greater than approximately 1.7 due to the likelihood of excessive variability in the results. The decision as to what gradation characteristics are to be considered too aggressive shall be made by the approval authority.

Regarding chemical properties of the environment surrounding the geosynthetic in the wall or slope, the pH shall be between 4.5 and 9 to be considered nonaggressive. This applies both in the reinforced backfill and at the back of the face of walls.

Regarding temperature, the effective design temperature at the wall or slope site shall be less than 30° C (85° F) for the environment to be considered nonaggressive. In all but the most southerly tier of states in the USA, all wall and slope sites are anticipated to have an effective design temperature that is below 30° C.

For most soil conditions in the USA, the environment will likely be chemically nonaggressive. A possible exception to this is immediately behind a concrete wall face, where pH levels could possibly be elevated above a pH of 9. However, recent research has indicated that for well drained backfills, the pH adjacent to a concrete face stays below 9 in the long-term (Koerner, et al., 2001, Koerner, et al., 2002). In any case, the long-term strength determination must account for the environment at the face. However, there are specific geological regions in the USA that are more likely to have chemically aggressive conditions as described in Elias (2000). Examples include salt affected soils in the arid western (especially southwest) regions of the USA, acid-sulphate soils that are commonly found in the Appalachian region of the USA, and calcareous soils commonly found in Florida, Texas, New Mexico, and many western states.

The wall or slope contract specifications will identify if the environment is anticipated to be aggressive and the reason for the aggressive environment designation (i.e., backfill gradation, site chemistry, or site temperature). If aggressive conditions are not identified in the contract specifications, and the contract specifications provide soil chemical criteria that are consistent with nonaggressive conditions as described herein, the environment should be considered to be nonaggressive to determine the longterm strength. However, the backfill should be tested prior to use to verify that it is nonaggressive.

4. Requirements for Class 1 Walls and Slopes to Determine T_{al}

RF_{ID} and RF_{CR} shall be determined from product specific data for all geosynthetics used in Class 1 walls and slopes. See submission requirements for installation damage and creep data provided in this document. The product specific data for these reduction factors shall be interpreted/extrapolated in accordance with Appendices A, B, and C. RF_D shall be determined from long-term product specific data, or a default value may be used as described below. See submission requirements for durability data provided herein. Long-term product specific data for RF_D should be interpreted in accordance with Appendix D. If adequate long-term durability data is not available, a default reduction factor for RF_D may be used if the environment is nonaggressive and if the product meets the minimum polymer and physical property requirements provided in Table 1. In this case, a default value for RF_D of 1.3 may be used for PET, HDPE, and PP geosynthetics.

Note 3: *The default value for RF_D of 1.3, which can be used for products that meet the minimum property requirements in Table 1, was determined based on FHWA (1997) and Elias, et. al. (1997) and in consideration of the relatively cool climate which exists in the state of Washington, where effective design temperatures are always less than 20° C (68° F) and are likely to be on the order of 10° C (50° F) or less. A higher default value of 1.5 for products which meet the property requirements in Table 1 may be desirable for more temperate climates which still meet the requirements for a nonaggressive environment, especially to address polyolefin oxidative degradation, as the potential for this type of degradation, even for products which meet the property requirements in Table 1, becomes more uncertain at higher temperatures due to the lack of protocols which can accurately identify the amount or effectiveness of end use antioxidants present. The UV resistance criteria provided in Table 1 only provides a rough indication of the effectiveness of end use antioxidants in polyolefins (see additional commentary following Table 1).*

If the environment is identified as aggressive due to the chemical regime or due to temperature, or if the geosynthetic product does not meet the requirements in Table 1, default reduction factors may not be used for RF_D . For chemically aggressive or elevated temperature environments, RF_D must be determined based on long-term product specific data for an environment that is as or more aggressive than the project specific environment in question. Aggressive environments need to be addressed in the product submittal only if specifically requested by the contracting agency or the geosynthetic supplier. Once the appropriate reduction factors are established, the long-term geosynthetic strength is determined using Equations 1 and 2, or as determined in Note 7 of Appendix B.

5. Requirements for Class 2 Walls and Slopes to Determine T_{al}

The strength reduction factors RF_{ID} , RF_{CR} , and RF_D may be determined based on product specific data as described for Class 1 walls and slopes. If long-term product specific data is not available, the environment is nonaggressive, and the product meets the minimum requirements provided in Table 1, a default value of 7 may be used for RF to determine the long-term strength of the product in accordance with Equations 1 and 2.

6. Minimum Polymer and Physical Property Requirements to Allow Use of Default Reduction Factors for RF and RF_D in Nonaggressive Environments

If a default reduction factor is to be used, geosynthetic products that are likely to have good resistance to installation stresses and to long-term chemical degradation are required to minimize the risk of significant long-term degradation. The physical and polymer material requirements provided in Table 1 must be met if detailed product specific data as described in Appendices A, B, C and/or D is not obtained. Polymer materials not meeting the requirements in Table 1 could be used if detailed product specific data extrapolated to the design life intended for the structure (see Appendices A, B, C and D) is provided.

Table 1

Minimum Requirements for Geosynthetic Products to Allow Use of Default Reduction Factor for Long-Term Degradation.

Polymer Type	Property	Test Method	Criteria to Allow Use of Default RF*
PP and HDPE	UV Oxidation Resistance	ASTM D4355	Min. 70% strength retained after 500 hrs in weatherometer
PET	UV Oxidation Resistance	ASTM D4355	Min. 50% strength retained after 500 hrs in weatherometer if geosynthetic will be buried within one week, 70% if left exposed for more than one week.
PP and HDPE	Thermo- Oxidation Resistance	ENV ISO 13438:1999, Method A (PP) or B (HDPE)	Min. 50% strength retained after 28 days (PP) or 56 days (HDPE)
PET	Hydrolysis Resistance	Inherent Viscosity Method (ASTM D4603 and GRI Test Method GG8), or Determine Directly Using Gel Permeation Chromatography	Min. Number Average Molecular Weight of 25,000
PET	Hydrolysis Resistance	GRI Test Method GG7	Max. Carboxyl End Group Content of 30
All Polymers	Survivability	¹ Weight per Unit Area (ASTM D5261)	¹ Min. 270 g/m ²
All Polymers	% Post-Consumer Recycled Material by Weight	Certification of Materials Used	Maximum of 0%

*Polymers not meeting these requirements may be used if product specific test results obtained and analyzed in accordance with Appendices A, B, C, and D are provided.

¹Alternatively, a default $RF_D = 1.3$ may be used if product specific installation damage testing is performed and it is determined that RF_{ID} is 1.7 or less, and if the other requirements in Table 1 are met.

Note 4: The requirements provided in Table 1 utilize currently available index tests and are consistent with current AASHTO design specifications (AASHTO, 2004, 2002), with the exception of the oven aging test, which is a new requirement. These index tests can provide an approximate measure of relative resistance to long-term chemical degradation of geosynthetics. Values selected as "minimum" criteria to allow use without additional long-term testing are based on values for such properties reported in the literature. These values are considered indicative of good long-term performance or represent a readily available current standard within the industry that signifies that a product has been enhanced for long-term environmental exposure.

Though UV resistance (i.e., photo-oxidation resistance) is not a direct indicator of thermo-oxidation resistance for polypropylene and polyethylene, both photo-oxidation and thermo-oxidation are oxidation reactions, and many UV inhibitors also provide at least some long-term resistance to thermo-oxidation (Van Zanten, 1986). Regarding polyester requirements, maximum resistance to strength losses due to hydrolysis can be obtained by formulating to high molecular weights (> 25,000) and low (i.e., < 30) Carboxyl End Group numbers (Risseeuw and Schmidt, 1990; FHWA, 1997; and Elias, et. al., 1997).

Minimum weight/area requirements are based on the results of numerous exhumations of geosynthetics, in which it was determined that installation damage was minimal for products with a minimum of weight of 270 g/m² (8 oz/yd²) (Koerner and Koerner, 1990; Allen, 1991). This roughly corresponds to a Class 1 geotextile as specified in AASHTO M-288.

There is little long-term history or even laboratory data regarding the durability of geosynthetics containing a significant percentage of recycled material. Therefore, their potential long-term performance is unknown, and it is recommended that long-term data be obtained for products with significant recycled material to verify their performance before using them.

Quality Assurance Requirements for Products that have been Through Initial Acceptance

1. Data Verification Requirements

The following information about each product shall be submitted for verification purposes:

- a. Geosynthetic type and structure.
- b. Spacing and dimensions of geogrid elements. The receiving laboratory should verify these dimensions upon receipt of the sample(s) using hand measurement techniques. This is especially critical for strength determination based on a single or limited number of ribs in the specimens tested.
- c. Polymer(s) used for fibers, ribs, etc.
- d. Polymer(s) used for coating, if present.
- e. Roll size (length, width, and area).
- f. Typical lot size.
- g. Polymer source(s) used for product.
- h. For HDPE and PP, primary resin ASTM type, class, grade, and category (for HDPE use ASTM D-1248, and for PP use ASTM D-4101).
- j. % post-consumer recycled material by weight.
- k. Minimum weight per unit area for product (ASTM D5261).
- l. MARV for ultimate wide width tensile strength (ASTM D4595 or ASTM D6637).

2. Quality Assurance (QA) Testing Approach

Results from index and performance tests will be compared to baseline index or performance test results obtained for initial product acceptance purposes. If the QA test results are within acceptable tolerances relative to the baseline results, the acceptance status of the product or product line will be maintained (e.g., the product will continue to be listed in the QPL). Re-testing must be done if there is any change in the product. If changes in the product identified through product data verification as described in part 1 above or identified through other means are such that the validity of the last complete assessment for initial acceptance is too questionable, a complete assessment of the product or product line in accordance with this Standard Practice instead of just a QA evaluation may be required by the approval authority to maintain acceptance status.

3. Quality Assurance (QA) Sampling

All materials and/or products to be tested will be furnished by the manufacturer/supplier at no cost to the review/approval authority. Samples will be selected for testing by Department of Transportation personnel or designated parties. As a minimum, the following shall be obtained:

- a geosynthetic product sample of sufficient size to accommodate all of the specified testing;
- information showing the manufacturer's name and description of product: (style, brand name, etc.);
- product roll and lot number;
- a sample of the polymer component(s) in sufficient quantity to conduct the specified polymer tests.

All samples for the specified QA testing shall be from the same roll of material for each product tested.

4. Quality Assurance (QA) Testing

Short-term ultimate tensile strength test results, and QA test results to verify the correctness of RF_{ID} , RF_{CR} , and RF_D determined from initial product acceptance testing, shall be obtained. Short-term tensile strength shall be determined in accordance with ASTM D4595 for geotextiles and ASTM D6637 for geogrids. QA testing required to verify the correctness of RF_{ID} , RF_{CR} , and RF_D determined from initial product acceptance testing is as follows:

A. Installation Damage Testing

For installation damage evaluation, a field exposure trial conducted in accordance with Appendix A shall be conducted for the product in the product line with the highest RF_{ID} from the initial product acceptance testing using the soil with a d_{50} size which is equal to or larger than a d_{50} size of 4.75 mm, or other d_{50} size as determined by the approval authority, and the aggregate shall have a maximum LA Wear percent loss of 35 percent. The d_{50} size, angularity, and durability of the selected backfill should be consistent with the d_{50} size used for initial product acceptance (preferably, the same material should be used for both the acceptance testing and the quality assurance testing, if possible). Alternatively, reduced scale laboratory installation

damage tests conducted in accordance with ISO/DIS 10722-1 may be used. In this case, these laboratory installation damage tests must also be conducted during initial product acceptance testing to establish a baseline value. The ultimate tensile strength of the lot or roll of material used in the installation damage testing obtained in accordance with ASTM D4595 or ASTM D6637 using the multi-rib procedure (or ISO 10319 if ISO/DIS 10722-1 is used) shall be obtained to normalize the installation damage test results in accordance with Appendix A. If it was determined during the initial product acceptance testing, for coated geogrids, that the installation damage factor was not a function of product weight or tensile strength, the coating weight shall also be evaluated. In this case, the mass/unit area of the sample tested shall be determined in accordance with ASTM D5261. The coating weight can then be established using the lot specific mass/unit area of the uncoated product from product manufacturer Quality Control (QC) data. The information required in part 2 of "Data Requirements for Initial Product Acceptance" as it applies to the QA testing shall be obtained and included in the test report for this QA testing.

B. Creep Testing

For creep rupture evaluation, a minimum of three creep-rupture points shall be obtained using SIM (ASTM D6992) or conventional ASTM D5262 tests (for which elevated test temperatures may be employed to accelerate creep – see Appendix B) at a load level established at the time of initial product acceptance testing that corresponds to a minimum rupture time of 100,000 hours at the reference temperature. If elevated temperature conventional creep testing using ASTM D5262 is performed, the shift factors obtained from the conventional creep testing for the temperatures used in the QA testing conducted for initial product acceptance shall be used to extrapolate the test data to the reference temperature. A fourth SIM test (or conventional ASTM D5262 test conducted at the reference temperature) shall be performed at a load level established at the time of initial product acceptance testing that corresponds to a minimum rupture time of 500 hours at the reference temperature. Note that if initial product acceptance was based on Appendix C (creep strain testing), creep strain measurements must be obtained, and the load levels selected for the QA creep testing should be equal to the load level that results in reaching a specified strain using the creep data used to establish the initial product acceptance envelope (see Appendix C, Section C.2.2) at 500 hours (one test) and 50,000 hours (three tests), at the reference temperature. The strain level used for this purpose shall preferably be 5 to 10% or more, and be as close to the instability limit strain as possible while catching as many of the creep curves as possible. See Section 5(d) for additional explanation.

For creep stiffness evaluation, if the product acceptance testing conducted indicates that the creep is log linear at the low strain levels tested, short-term (1,000 second) ramp and hold (R+H) tests as described in ASTM D6992 may be used and extrapolated to 1,000 hours in lieu of 1,000 hour creep tests. A minimum of two R+H tests shall be conducted for one product in the product line at the load level in which 2 percent strain at 1,000 hours was achieved in the product acceptance testing. If the product acceptance testing indicates that the creep is not log linear at the low strain level tested, then a minimum of two full 1,000 hour creep tests must be conducted at that load level. These tests shall be conducted on the same width specimens as was used for the product acceptance creep stiffness testing.

If SIM is used for this creep rupture testing, it shall have been demonstrated for the initial acceptance testing that the reduced specimen width typically used for SIM testing does not have a significant effect on the creep rupture results, and provided that the validity of SIM for the product through comparison of SIM data with “conventional” creep rupture data was established for the initial product acceptance testing.

The ultimate tensile strength of the lot or roll of material used in the creep testing obtained in accordance with ASTM D4595 or ASTM D6637 shall be obtained to normalize the creep rupture loads in accordance with Appendix B or C. The information required in part 3 of “Data Requirements for Initial Product Acceptance” as it applies to the QA testing shall be obtained and included in the test report for this QA testing.

Note 5: If “conventional” creep testing is performed for QA purposes, it is assumed that the product has not changed relative to what was tested for initial product acceptance purposes, thereby allowing the assumption to be made that the shift factors obtained through the initial product acceptance testing are valid for the QA testing. Requiring new “conventional” creep test shift factors to be re-established would result in the need to fully repeat the test program for the initial product acceptance, which would not be practical for QA purposes. Regarding the fourth creep test data point, the requirement to use only data obtained at the reference temperature if “conventional” creep testing is performed provides a second check that eliminates the need for this shift factor assumption and any inaccuracies associated with that assumption.

C. Durability Testing

If only index durability testing was conducted to allow use of a default value for RF_D for the initial product acceptance testing, only index durability testing need be conducted for QA purposes. In this case, durability testing for QA purposes shall consist of the determination of molecular weight based on GRI-GG7 and carboxyl end group content based on GRI-GG8 for polyesters, UV resistance based on ASTM D4355 for polyolefins and PET's), and an oven aging exposure test per ENV ISO 13438:1999 for polyolefin geosynthetics. Regarding the oven aging test, control and post-exposure specimens shall be tested for tensile properties (ASTM D4595 or ASTM D6637). The results of this oven aging testing will be used only to compare a product with itself, and to meet the minimum requirements in Table 1. In addition, geogrid brittleness shall be evaluated per WSDOT Test Method T 926.

If long-term performance durability testing was conducted to justify the use of a lower RF_D or to justify use in aggressive environments for initial product acceptance, a minimum of five specimens shall be exposed to the most aggressive environment used in the initial product acceptance testing at the highest temperature tested, for a minimum of 2,000 hours. These specimens, and unexposed specimens from the same roll of material, shall be tested for tensile properties (ASTM D4595 or ASTM D6637). In addition, for polyolefins, either oxidative induction time per ASTM D 3895 or high pressure oxidative induction time per ASTM D 5885 shall be conducted for each specimen tested (before and after exposure), and for PET's, molecular weight (ASTM D4603 and GRI:GG8) and specimen weight per unit area (ASTM D5261) shall be conducted for each specimen tested (before and after exposure).

5. Quality Assurance (QA) Criteria for Comparison to Initial Product Acceptance Test Results

The acceptability of the QA test results to allow a product or product line to maintain its prior acceptance status is established based on the statistical significance, or lack thereof, of the difference between the QA test results and the initial product acceptance test results. The criteria and methods for determining the statistical significance between the QA and initial product acceptance test results are as follows:

A. Short-term Index Tensile Testing

For wide width tensile strength, the mean of the test results for the sample for each product tested shall be greater than or equal to the MARV reported for the product.

B. Installation Damage Testing

If the mean of the average strength of the sample after damage as a percent of the undamaged strength is less than the average value obtained for the same product and condition during the product acceptance phase, the maximum difference between the two means shall be no greater than what is defined as statistically insignificant based on a one-sided student-t distribution at a level of significance of 0.05. In this case, t is determined as follows:

$$t_{\alpha/2,n_1+n_2-2} = \frac{(\bar{P}_1 - \bar{P}_2) - \delta}{\sqrt{\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{(n_1+n_2)}}} \sqrt{\frac{n_1 n_2 (n_1 + n_2 - 2)}{(n_1 + n_2)}}$$

where,

$t_{\alpha/2,n_1+n_2-2}$	= value of the t-distribution for the installation damage samples
P_1	= the mean of the strength retained after installation damage (i.e., $T_{\text{dam}}/T_{\text{lot}}$) obtained for initial product acceptance
P_2	= the mean of the strength retained after installation damage (i.e., $T_{\text{dam}}/T_{\text{lot}}$) obtained for QA testing
δ	= the difference in the means for the populations corresponding to the sample means P_1 and P_2 (assumed equal to zero for this test)
s_1	= the standard deviation corresponding to P_1
s_2	= the standard deviation corresponding to P_2
n_1	= the number of data points corresponding to P_1
n_2	= the number of data points corresponding to P_2

$t_{\alpha/2,n_1+n_2-2}$ calculated using Equation 3 shall be no greater than t determined from the applicable Student t table (or from the Microsoft EXCEL function TINV($\alpha, n-2$)) at $\alpha = 0.05$ and n_1+n_2-2 degrees of freedom. If this is not true, the difference between P_1 and P_2 is determined to be statistically significant, and $P_1 > P_2$, two additional samples from the same installation condition shall be tested and P_2 recalculated and statistically compared to P_1 . If the QA test results are still too low, a full installation damage study for initial product acceptance must be completed in accordance with Appendix A, and new values of RF_{ID} established.

C. Creep Rupture Testing for Prediction of Creep Limit

For creep evaluation, the four creep-rupture points, one at a load level that results in an approximate rupture time, after time shifting, of 500 hours and three at a load level that results in an approximate rupture time, after time shifting, of 100,000 hours on the rupture envelope obtained for initial product acceptance purposes shall be compared to the creep data obtained for initial product acceptance purposes. The log of the rupture time for each of these four rupture points shall be equal to or greater than the 95% lower prediction limit of the variable, log time, established by the Student's t test of the original product acceptance data set.

The prediction limit for the regression performed for initial product acceptance is given by (Wadsworth, 1998):

$$\log t_L = \log t_{reg} - \left[t_{\alpha/2,n-2} \sqrt{1 + \frac{1}{n} + \frac{(P - \bar{P})^2}{\sum (P_i - \bar{P})^2}} \right] \times \sigma$$

and

$$\sigma = \sqrt{\frac{\sum [\log t_i - \bar{\log t}]^2 - \frac{\sum [(P_i - \bar{P})(\log t_i - \bar{\log t})]^2}{n-2}}{n-2}} \quad (5)$$

where:

- $\log t_L$ = lower bound prediction limit
- t_{reg} = time corresponding to the load level from the initial product acceptance creep rupture envelope at which QA creep tests were performed (e.g., at 500 and 100,000 hrs after time shifting)
- $t_{\alpha/2,n-2}$ = value of the t distribution determined from applicable Student t table (or from the Microsoft EXCEL function TINV(α , $n-2$) at $\alpha/2 = 0.05$ and $n-2$ degrees of freedom (this corresponds to the 95% one-sided prediction limit))
- n = the number of rupture or allowable run-out points in the original test sample (i.e., for initial product acceptance)
- P = load level obtained at t_{reg} from the regression line developed from the initial product acceptance testing
- \bar{P} = the mean rupture load level for the original test sample (i.e., all rupture or run-out points used in the regression to establish the rupture envelope for initial product acceptance)
- P_i = the rupture load level of the i 'th point for the rupture points used in the regression for establishing the rupture envelope for initial product acceptance
- $\log t$ = the mean of the log of the rupture time for the original test sample (i.e., all rupture or run-out points used in the regression to establish the rupture envelope for initial product acceptance)
- t_i = the rupture time of the i 'th point for the rupture points used in the regression for establishing the rupture envelope for initial product acceptance

The comparison between the QA test results and the initial product acceptance test results is illustrated conceptually in Figure 1. Once $\log t_L$ has been determined at each specified load level, compare this value to the log rupture time (i.e., $\log t_{QA}$) obtained for each QA creep rupture test at the specified load level (e.g., 500 and 100,000 hours). If $\log t_{QA} < \log t_L$ for any of the QA creep rupture test results, perform two additional tests at the load level P for the specified t_{reg} where this QA criteria was not met and compare those results to $\log t_L$. If for these two additional tests this criterion is not met, perform adequate additional creep rupture testing to establish a new rupture envelope for the product in accordance with initial product acceptance requirements (Appendix B). This new rupture envelope will form the baseline for any future QA testing.

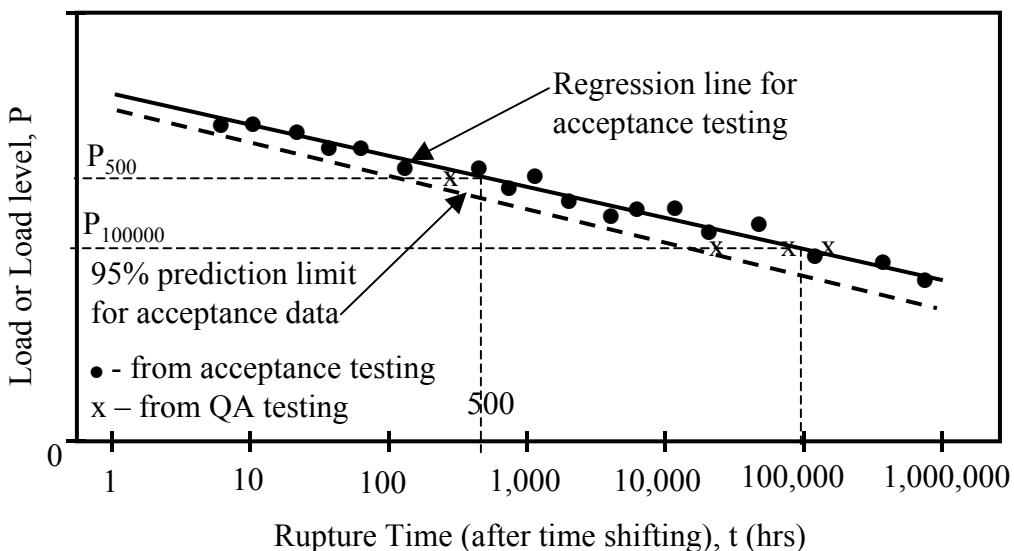


Figure 1. Conceptual illustration of the comparison of QA creep rupture test results to initial product acceptance creep rupture test results.

D. Creep Strain Testing for Prediction of Creep Limit

The comparison between the creep data obtained for the initial product acceptance testing and the QA creep data shall be performed at a specified strain. The specified strain will depend on the strains observed in all of the creep tests (initial product acceptance and QA). Select a strain that will intercept all of the creep curves as much as possible. Preferably, the strain level should be approximately 5 to 10% or more, and as close to the instability limit strain as possible. Where the selected strain level intersects each creep curve, determine the time required to reach the specified strain. Plot the load level as a function of the logarithm of time to reach the specified strain for the initial product acceptance data, and perform a regression for this data set.

The log times to the specified strain level for the QA creep data shall be determined at a load level that corresponds to 500 hours and 50,000 hours on the initial product acceptance creep envelope. This is illustrated conceptually in Figure 2. The log of the time to reach the same specified strain for each of the four QA creep data points shall be equal to or greater than the 95% lower prediction limit of the variable, log time, established by the Student's t test of the original product acceptance data set, using Equations 4 and 5 (see part "c" above).

Once $\log t_L$ has been determined at each specified load level, compare this value to the log time to reach the specified strain (i.e., $\log t_{QA}$) obtained for each QA creep test at the specified load level (e.g., 500 and 50,000 hours). If $\log t_{QA} < \log t_L$ for any of the QA creep rupture test results, perform two additional tests at the load level P for the specified t_{reg} where this QA criteria was not met and compare those results to $\log t_L$. If for these two additional tests this criterion is not met, perform adequate additional creep testing to establish a new creep stiffness curve for the product in accordance with initial product acceptance requirements (Appendix C). This new creep stiffness curve will form the baseline for any future QA testing.

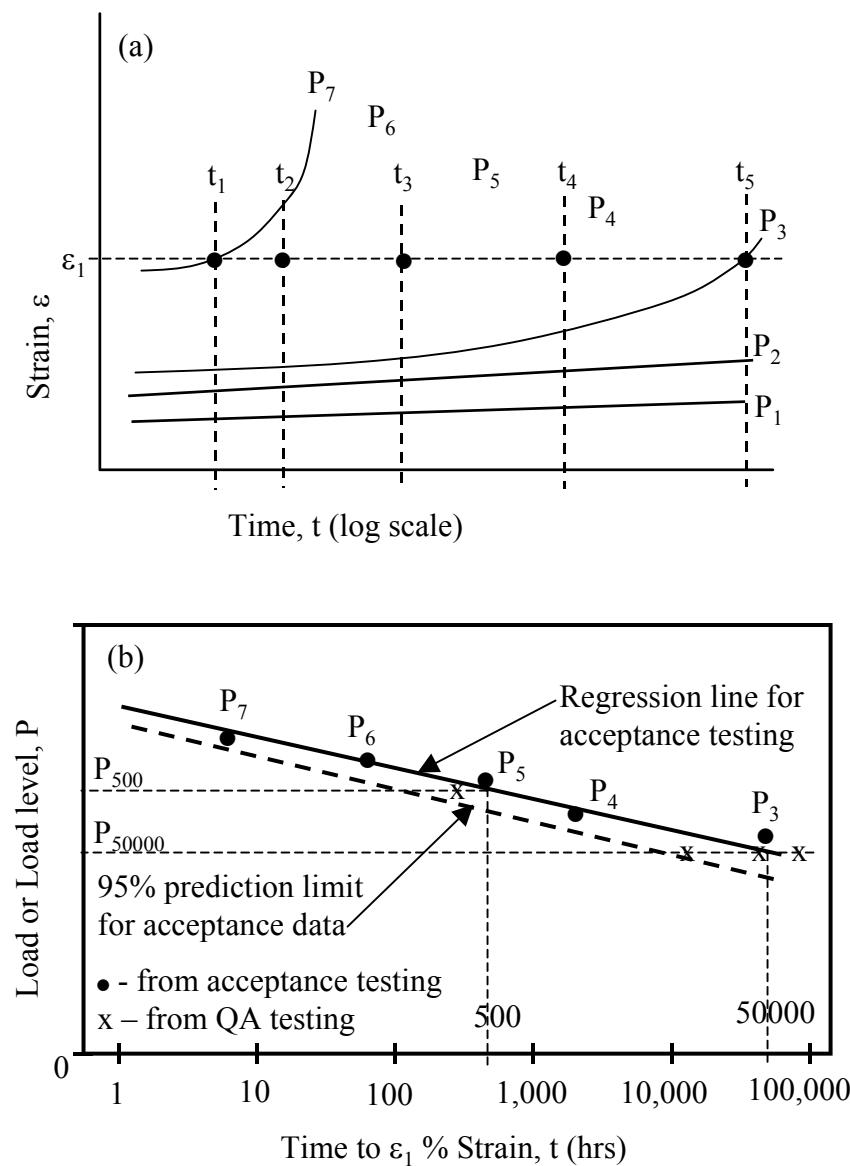


Figure 2. Conceptual illustration of the comparison of QA creep strain test results to initial product acceptance creep strain test results (a) creep strain curves, and (b) envelope of time to the specified strain.

E. Assessment of the Creep Stiffness at Low Strain

The comparison between the creep data obtained for the initial product acceptance testing and the QA creep data shall be performed at a specified strain, in this case typically 2%. Where the selected strain level intersects each creep curve, determine the time required to reach the specified strain. Plot the load level as a function of the logarithm of time to reach the specified strain for the initial product acceptance data, and perform a regression for this data set. The log times to the specified strain level for the QA creep data shall be determined at a load level that corresponds to 1,000 hours on the initial product acceptance creep curve. The estimated time to reach the same specified strain for each of the two QA creep data points shall be equal to or greater than the 95% lower prediction limit of the variable, log time, established by the Student's *t* test of the original product acceptance data set, using Equations 4 and 5 (see part "c" above).

Once $\log t_L$ has been determined at the specified load level, compare this value to the log time to reach the specified strain (i.e., $\log t_{QA}$) obtained for each QA creep test at the specified load level (e.g., 1,000 hours). If $\log t_{QA} < \log t_L$ for any of the QA creep rupture test results, perform two additional tests at the same load level *P* for the specified strain and compare those results to $\log t_L$. If for these two additional tests this criterion is not met, perform adequate additional creep testing to establish a new low strain creep stiffness value for the product in accordance with initial product acceptance requirements (Appendix C). This new low strain creep stiffness value will form the baseline for any future QA testing.

F. Durability Testing

For UV resistance (all polymers), molecular weight and CEG (PET only), and oven aging (PP and HDPE), the QA test results shall meet the minimum requirements provided in Table 1. For the oven aging tests (polyolefins only), compare the tensile strength retained (i.e., strength after oven exposure divided by the strength of the control specimens) to the strength observed during initial product acceptance testing. The maximum difference between the values of the changes shall be no greater than what is defined as statistically insignificant based on a one-sided student-*t* distribution at a level of significance of 0.05, as determined using Equation 3. In this case, P_1 and P_2 are defined as the strength retained after oven aging.

$t_{\alpha/2,n_1+n_2-2}$ calculated using Equation 3 shall be no greater than *t* determined from the applicable Student *t* table (or from the Microsoft EXCEL function TINV($\alpha,n-2$)) at $\alpha/2 = 0.05$ and n_1+n_2-2 degrees of freedom. If this is not true, and the difference between P_1 and P_2 is determined to be statistically significant, and $P_1 > P_2$, two additional samples from the same installation condition shall be tested and recalculated and statistically compared to P_1 . If the QA test results are still unacceptable, or if the product loses more than 50% of its tensile strength during the QA test, a more complete investigation performed in accordance with Appendix D shall be performed.

If long-term performance durability testing was conducted to justify the use of a lower RF_D or to justify use in aggressive environments for initial product acceptance, the statistical methodology and criteria provided above for index oven aging (i.e., that there be no statistically significant difference between the initial product acceptance test results and the QA test results at a level of significance of 0.05) shall be applied to the oxidation or hydrolysis performance test results at the maximum exposure time and environmental conditions used for the OA testing.

References

- AASHTO, 2002, *Standard Specifications for Highway Bridges*, American Association of State Highway and Transportation Officials, Seventeenth Edition, Washington, D.C., USA.
- AASHTO, 2004, *LRFD Bridge Design Specifications, with Interims*, American Association of State Highway and Transportation Officials, Third Edition, Washington, D.C., USA.
- Allen, T.M., 1991, "Determination of Long-Term Strength of Geosynthetics: a State-of-the-Art Review", *Proceedings of Geosynthetics '91*, Atlanta, GA, USA, Vol. 1, pp. 351-379.
- Elias, V., 2000, Corrosion/Degradation of Soil Reinforcements for Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, FHWA-NHI-00-044, Federal Highway Administration, Washington, D.C.
- Elias, V., DiMaggio, J., and DiMillio, A., 1997, "FHWA Technical Note on the Degradation-Reduction Factors for Geosynthetics," *Geotechnical Fabrics Report*, Vol. 15, No. 6, pp. 24-26.
- Federal Highway Administration (FHWA), 1997, "Degradation Reduction Factors for Geosynthetics," *Federal Highway Administration Geotechnology Technical Note*.
- Geosynthetic Research Institute, 1998, "Carboxyl End Group Content of Polyethylene Terephthalate (PET) Yarns," GRI Test Method GG7.
- Geosynthetic Research Institute, 1998, "Determination of the Number Average Molecular Weight of Polyethylene Terephthalate (PET) Yarns based on a Relative Viscosity Value," GRI Test Method GG8.
- Koerner, G. R., Hsuan, Y. G., and Hart, M., 2001, *Field Monitoring and Laboratory Study of Geosynthetics in Reinforcement Applications*, GRI Report #26, Geosynthetic Research Institute, Drexel University, Philadelphia, PA, USA, 116 pp.
- Koerner, G. R., Hsuan, Y. G., and Koerner, R. M., 2002, "Field Measurements of Alkalinity (pH) Levels Behind Segmental Retaining Walls, or SRW's," *7th International Geosynthetics Conference*, Nice, France, Delmas, Gourc, and Girard, ed's, Vol. 4, pp. 1443-1446.
- Koerner, R. M. and Koerner, G. R., 1990, "A quantification and assessment of installation damage to geotextiles." *Proc. Fourth Intl. Conf. on Geotextiles, Geomembranes, and Related Products*, The Hague, pp. 597-602.
- Risseeuw, P. and Schmidt, H. M., 1990, "Hydrolysis of HT Polyester Yarns at Moderate Temperatures," *Proceedings of the Fourth International Conference on Geotextiles, Geomembranes, and Related Products*, The Hague, pp. 691-696.
- Sprague, C. J., Allen, S., and Thornton, S., 1999, "Installation Damage Testing, Sensitivity Assessment and Derivation of RF_{ID}," *Geosynthetics '99*, Boston, MA, USA, pp. 1123-1132.
- Van Zanten, V., ed., 1986, *Geotextiles and Geomembranes in Civil Engineering*, Wiley-Halsted.
- Wadsworth, H., 1998, *Handbook of Statistical Methods for Engineers and Scientists*, McGraw-Hill, 688 pp.

WSDOT Test Method No. 925, Appendix A

Product Specific Testing and Data Interpretation Requirements to Determine RF_{ID} for Geosynthetic Reinforcements

The effect of installation damage on geosynthetic reinforcement strength and deformation shall be determined from the results of full scale installation damage tests in accordance with ASTM D5818, except as modified herein:

1. The locations of specimens within the sample to be removed for testing after installation and exhumation should be predetermined before installation through the use of a template. The specimens shall be large enough to be used for wide width testing (ASTM D4595 for geotextiles or ASTM D6637, specimen preparation method B or C for geogrids). A minimum of 20 specimen locations should be identified using a template for each installation condition evaluated. No specimen should be located closer than 150 mm (6 in.) from the edge of the sample. The locations of the specimens should be evenly distributed throughout the sample. Each specimen should be consecutively numbered before installation. The sample size shall be large enough to obtain the minimum number of specimens (i.e., 20) of the required dimensions.
2. Place and compact 150 mm (6 in.) or more of soil (same soil as used to cover the geosynthetic) on a flat, level, relatively incompressible subgrade. The compacted layer shall simulate the roughness and compressibility of the backfill conditions in which the geosynthetic layer is likely to be placed in full scale structures.
3. Place the geosynthetic on top of the compacted soil pad. The geosynthetic shall pulled taught with no wrinkles or folds. It may be necessary to pin the corners of the geosynthetic to maintain its position as soil is placed over the geosynthetic.
4. Place and compact 150 to 200 mm (6 to 8 in.) of backfill material (or other previously agreed upon depth to simulate actual installation conditions likely to be encountered) over the geosynthetic using the type of spreading and compacting equipment that is likely to be used in full scale structures. The backfill should be compacted to a minimum of 90 percent of Modified Proctor per ASTM D1557, or to another compaction standard typically used for geosynthetic reinforced structures if agreed upon in advance by the approval authority.
5. The sample shall be removed from the compacted fill in a way that minimizes damage to the sample caused by the excavation process. The sample removal process is generally described in ASTM D5818. In addition to the removal methods described therein, a lifting plate may be placed below the compacted soil pad below the geosynthetic layer as described in Sprague and Allen (2003) to facilitate easy removal of the soil above the geosynthetic.
6. The first nine prenumbered specimens identified on the exhumed sample shall be selected for testing. If any of these specimens were damaged due to the exhumation process, that specimen(s) shall be skipped, and the next consecutively numbered specimen(s) shall be selected for testing. If the coefficient of variation for the tensile test results of these first nine prenumbered specimens is greater than 5%, the required number of specimens shall be recomputed using the one-sided student t distribution as required by ASTM D4595 or ASTM D6637. The additional specimens shall be

7. Samples subjected to installation damage shall be tested for tensile strength and deformation characteristics in accordance with ASTM D4595, or ASTM D6637. The number of specimens tested should be in accordance with ASTM D4595 or D6637. Single rib tests such as GRI:GG1 shall not be used for installation damage evaluation, as it is difficult to assess the effect of severed ribs on the strength and stiffness of damaged materials. Test results from damaged specimens shall 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.

8. The installation damage reduction factor RF_{ID} is then determined as follows:

$$RF_{ID} = \frac{T_{lot}}{T_{dam}} \quad (A-1)$$

where, T_{lot} is the average lot specific tensile strength before exposure to installation, and T_{dam} is the average lot specific tensile strength after installation. In no case should RF_{ID} be less than 1.1.

9. To select an appropriate reduction factor for design, the project site installation conditions must be related to the installation test conditions. To relate the installation damage test conditions to the actual site conditions, primary consideration will be given to the backfill characteristics (d₅₀ particle size, potential for oversize material, particle angularity, and overall gradation), and to a lesser degree the method of spreading the backfill over the geosynthetic, the type of compaction equipment, and initial backfill lift thickness over the geosynthetic, provided that the initial lift thickness is 150 mm (6 in.) or more. The actual installation conditions used in the test must be clearly stated in the test report, specifically identifying any deviations from typical geosynthetic reinforcement installation practices in full scale structures, and the impact those deviations may have on the values of RF_{ID} determined. Typical installation conditions, for the purposes of this protocol, are generally described as follows:

- The geosynthetic is placed on a subgrade prepared as described in step 2.
- Backfill material is placed and spread on the geosynthetic using full scale spreading and compaction equipment commonly used in wall or reinforced slope construction (e.g., loaded dump trucks, dozers such as a D-6 or larger, etc.).
- Backfill is compacted using a full scale vibratory drum roller (i.e., one that someone can drive, not a smaller walk behind unit typically used to compact near the face of a wall to prevent distortion of facing elements during compaction).

If it is not possible to conduct the installation damage test in a way that fully simulates these “typical” installation conditions (i.e., installation conditions in the test are less severe than the conditions described above, for example, use lighter equipment, less movement of soil over the geosynthetic as the backfill is spread, etc.), data must be provided that demonstrates the effect the use of these less severe installation conditions would have on RF_{ID} .

10. If the installation damage test is conducted for a specific project, the actual backfill material planned for use in the geosynthetic structure should be used for the test. If the purpose of the installation damage testing is to generate RF_{ID} values for general use for future projects (i.e., the testing is not intended to be project specific), a range of soil backfill gradations/types should be used in the testing. The range of backfill materials selected should permit interpolation as needed to match the specific soil to be used as reinforced soil backfill. In general, the backfill materials tested should range from soil classified as a sand to coarse gravel (e.g., d_{50} sizes ranging from 0.5 to 25 mm). The backfill materials selected should be angular to subangular and shall be durable. The coarse sand and gravel portions of the backfill material should have a Los Angeles Wear (LA Wear) percent loss after 500 revolutions (AASHTO T96) of no more than 35 percent. Additional installation damage tests may be conducted with a less durable backfill material, at the discretion of the manufacturer and the approval authority. If tests are conducted using a backfill material that does not meet the LA Wear requirement stated above, the condition of the backfill shall be evaluated for changes in angularity and gradation after each use. If changes in these two parameters are observed, the aggregate shall be immediately replaced with fresh material. This gradation/angularity evaluation should be conducted periodically even for more durable backfill material. Note that if the backfill materials available in the region for which the approval authority has jurisdiction consistently cannot meet the maximum LA Wear requirement of 35 percent loss, a less durable aggregate may be used for all the backfill materials tested, at the discretion of the approval authority.
11. Values of RF_{ID} may be estimated for a specified soil gradation using interpolation as illustrated in Figure A-1. The d_{50} size of the soil has commonly been used for interpolating between soil backfills for determination of RF_{ID} . Other combinations of soil particle size and factors that account for soil angularity and durability may be considered for this correlation and interpolation procedure per mutual agreement between the geosynthetic manufacturer and the approval authority. The range of backfill gradations, angularity, and durability will affect the range of applicability of the RF_{ID} values obtained from the testing. RF_{ID} values should not be extrapolated beyond the coarsest backfill soil tested.

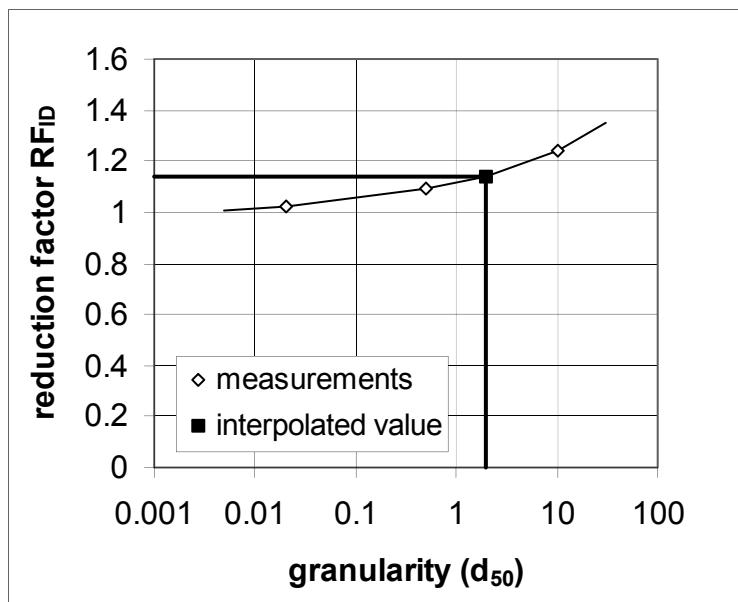
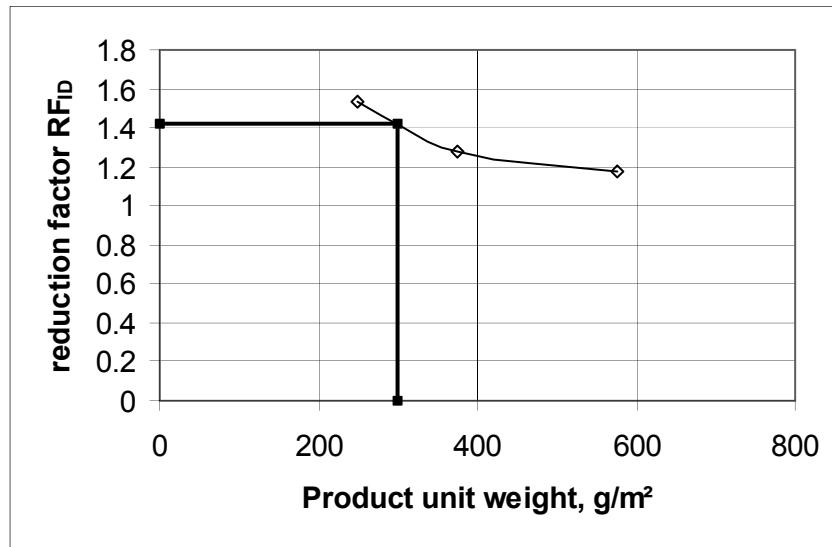


Figure A-1. Interpolation of RF_{ID} for a soil with $d_{50} = 2$ mm from installation damage data obtained for soils with $d_{50} = 0.02, 0.5$ and 10 mm (Note: 1in. = 0.0254 mm).

12. Not all products within a product line need to be tested for installation damage. As a minimum, the weakest (lightest) and strongest (heaviest) products within the product line, plus at least one additional intermediate strength (weight) product should be used to characterize RF_{ID} for the product line (note: if the strongest product within the product line is not tested, all heavier products will be assumed to have the same value of RF_{ID} as the heaviest product tested). An example of this interpolation procedure is provided in Figure 2. For coated polyester geogrids, the coating thickness or coating mass per unit area relative to the mass per unit area of the product should be considered for the purpose of correlating RF_{ID} between products rather than product unit weight or tensile strength alone. It is acceptable to obtain the coating mass/unit area through the use of manufacturer Quality Control (QC) data on the lot specific mass/unit area of the uncoated material (i.e., the weight of the “greige-good”), subtracting that mass/unit area from the total mass/unit area of the finished product. Therefore, the total mass per unit area of the sample used in the installation damage testing should be obtained in accordance with ASTM D5261.



Figure, A-2. Example interpolation of RF_{ID} from damage measurements on products from the same line but with different weights. For a product of weight $300 \text{ g}/\text{m}^2$, $\text{R F}_{\text{ID}} = 1.42$ (Note: $1 \text{ oz}/\text{yd}^2 = 0.0295 \text{ gm}/\text{m}^2$).

If it is determined that the RF_{ID} values obtained for a product line are not correlated with product weight per unit area, undamaged tensile strength, coating weight, or some other product parameter, and the variance of RF_{ID} between any two products in the product line is 0.1 or more, then each product in the product line shall be tested. If in this case (i.e., no correlation could be found), the variance of RF_{ID} between any two products in the product line is less than 0.1 and the upper bound value of RF_{ID} is selected for all products in the product line, all products in the product line do not need to be tested.

References

- Sprague, C. J., Allen, S. A., 2003, "Testing Installation Damage of Geosynthetic Reinforcement," Geotechnical Fabrics Report, Vol. 21, No. 6, pp. 24-27.

WSDOT Test Method No. 925, Appendix B

Creep Rupture Testing and Extrapolation Procedures

The effect of long-term load/stress on geosynthetic reinforcement strength and deformation characteristics shall be determined from the results of product specific, controlled, long-term laboratory creep tests conducted for a range of load levels and durations in accordance with ASTM D5262 adequate for extrapolation purposes to the desired design life, carried out to rupture of the geosynthetic when possible. Creep testing in accordance with ASTM D5262, but carried out to rupture where feasible, is described herein as the “conventional method.” A limited number of conventional creep tests may be supplemented and extended to longer creep rupture times using ASTM D6992 (Stepped Isothermal Method, or SIM) as described in this appendix. Specimens should be tested in the direction in which the load will be applied in use. Test results shall be extrapolated to the required structure design life. Based on the extrapolated test results, for ultimate limit state design, determine the highest load level, designated T_1 , which precludes both ductile and brittle creep rupture within the required lifetime. T_1 should be determined at the required design life and at the design site temperature.

In both cases, unless otherwise specified or mutually agreed upon by the geosynthetic supplier, the testing laboratory, and the owner, a baseline testing temperature of 68° F (20° C) shall be used for this testing. Higher test temperatures shall be considered as elevated temperatures to be used for the purpose of time extrapolation. ASTM D5262 requires that the testing temperature be maintained at +3.6° F (2° C). For some polymers, this degree of variance could significantly affect the accuracy of the shift factors and extrapolations determined in accordance with this appendix. For polymers that are relatively sensitive to temperature variations, this issue should be considered when extrapolating creep data using time-temperature superposition techniques, or minimized by using a tighter temperature tolerance.

Note that the procedures provided in this appendix are for in-air creep rupture testing. The procedures provided herein can likely also be applied to creep tests conducted confined in-soil. However, there is little information available, at present, on which to confirm that these procedures can be applied to in-soil creep data without modification. Therefore, procedures for use and interpretation of in-soil creep testing in compliance with this standard practice are not provided.

Single ribs for geogrids, or yarns or narrow width specimens for woven geotextiles, may be used for creep testing for the determination of RF_{CR} provided that it can be shown through a limited creep testing program conducted as described in Section B.5 later in this appendix that the rupture behavior and envelope for the single ribs, yarns, or narrow width specimens are the same as that for the full width product, with product width as defined in ASTM D5262. This comparison must demonstrate that there is no statistical difference between the full width product creep rupture regression line and the single rib, yarn, or narrow width specimen regression line at a time of 1,000 hours using a student-t distribution at a confidence level of 0.10 (see Equation B.3-1 later in this appendix).

Note 1: Creep results in time dependent deformation that may continue to occur as long as the reinforcement is loaded. At low to intermediate load levels, depending on the polymer type, the creep rate will continue to decrease with time and may eventually stabilize, at least within the ability to measure creep. At higher load levels, creep will continue until rupture occurs.

In general, two types of creep tests are conducted: stress or creep rupture, and creep strain. Creep strains do not have to be monitored in creep rupture testing (strain measurement in this type of test is recommended, however), though creep strain tests can be carried to rupture. Rupture data is necessary if the creep reduction factor for ultimate limit state conditions, RF_{CR} , is to be determined. Creep rupture test results, if properly accelerated and extrapolated, can also be used to investigate the effects of stress cracking and the potential for a ductile to brittle transition to occur. This transition to brittle behavior, if it occurs, can cause a geosynthetic to fail in creep at lower loads and strains than anticipated from evaluating only creep strain and rate data.

B.1 Overview of Extrapolation Approach to Determine the Ultimate Limit State Creep Limit, T_1

Considering that typical design lives for permanent MSE structures are 75 years or more, extrapolation of creep data will be required. Current practice allows creep data to be extrapolated up to one log cycle of time beyond the available data without some form of accelerated creep testing, or possibly other corroborating evidence (Jewell and Greenwood, 1988; Koerner, 1990). Based on this, unless one is prepared to obtain 7 to 10 years of creep data, temperature accelerated creep data, or possibly other corroborating evidence, must be obtained.

It is well known that temperature accelerates many chemical and physical processes in a predictable manner. In the case of creep, this means that the creep strains under a given applied load at a relatively high temperature and relatively short times will be approximately the same as the creep strains observed under the same applied load at a relatively low temperature and relatively long times. Temperature affects time to rupture at a given load in a similar manner. This means that the time to a given creep strain or to rupture measured at an elevated temperature can be made equivalent to the time expected to reach a given creep strain or to rupture at in-situ temperature through the use of a time shift factor.

The ability to accelerate creep with temperature for polyolefins such as polypropylene (PP) or high density polyethylene (HDPE) has been relatively well defined (Takaku, 1981; Bush, 1990; Popelar, et. al., 1991). Also for polyolefins, there is some risk that a “knee” in the stress rupture envelope due to a ductile to brittle transition could occur at some time beyond the available data (Popelar, et. al., 1991). Therefore, temperature accelerated creep data is strongly recommended for polyolefins. However, in practice, a ductile to brittle transition for polyolefin geosynthetic reinforcement products has so far not been observed, likely due to the highly oriented nature of polymer resulting from the processing necessary to make fibers and ribs. In general, the degree of orientation of the polymer is an important factor regarding the potential for ductile to brittle transitions.

For polyester (PET) geosynthetics, available evidence indicates that temperature can also be used to accelerate PET creep, based on data provided by den Hoedt, et. al., 1994 and others. However, the creep rupture envelopes for PET geosynthetics tend to be flatter than polyolefin creep rupture envelopes, and accurate determination of time-shift factors can be difficult for PET geosynthetics because of this. This may require greater accuracy in the PET stress rupture data than would be required for polyolefin geosynthetics to perform accurate extrapolations using elevated temperature data. This should be considered if using elevated temperature data to extrapolate PET stress rupture data. Note that a “knee” in the stress rupture envelope of PET does not appear to be likely based on the available data and the molecular structure of polyester.

If elevated temperature is used to obtain accelerated creep data, it is recommended that minimum increments of 10° C be used to select temperatures for elevated temperature creep testing. The highest temperature tested, however, should be below any transitions for the polymer in question. If one uses test temperatures below 70 to 75° C for polypropylene (PP), high density polyethylene (HDPE), and PET geosynthetics, significant polymer transitions will be avoided. If higher temperatures must be used, the effect of any transitions on the creep behavior should be carefully evaluated. One should also keep in mind that at these high temperatures, significant chemical interactions with the surrounding environment are possible, necessitating that somewhat lower temperatures or appropriate environmental controls be used. These chemical interactions are likely to cause the creep test results to be conservative. Therefore, from the user’s point of view, potential for chemical interactions is not detrimental to the validity of the data for predicting creep limits. However, exposure to temperatures near the upper end of these ranges could affect the stress-strain behavior of the material due to loss of molecular orientation, or possibly other effects that are not the result of chemical degradation. Therefore, care needs to be exercised when interpreting results from tests performed at temperatures near the maximum test temperatures indicated above. In general, if the stiffness of the material after exposure to the environment is significantly different from that of the virgin material, the stress-strain properties, and possibly the strength, of the material may have been affected by the exposure temperature in addition to the chemical environment. If the stiffness has been affected, the cause of the stiffness change should be thoroughly investigated to determine whether or not the change in stiffness is partially or fully due to the effect of temperature, or alternatively not use the data obtained at and above the temperature where the stiffness was affected.

Unless otherwise specified or required by site specific temperature data, an effective design temperature of 20° C (T_{amb}) should be assumed.

A number of extrapolation and creep modeling methods have been reported in the literature (Findley, et. al., 1976; Wilding and Ward, 1978; Wilding and Ward, 1981; Takaku, 1981; McGown, et. al., 1984; Andrawes, et. al., 1986; Murray and McGown, 1988; Bush, 1990; Popelar, et. al., 1991; Helwany and Wu, 1992). Many of the methods discussed in the literature are quite involved and mathematically complex.

Two creep extrapolation techniques are provided herein for creep rupture evaluation: the conventional method, which utilizes a simplified visual/graphical approach, temperature acceleration of creep, regression techniques, and statistical extrapolation, and the Stepped Isothermal Method (SIM). This does not mean that the more complex mathematical modeling techniques cannot be used to extrapolate creep of geosynthetics; they are simply not explained herein. These two techniques are described in more detail as follows:

B.2 Step-By-Step Procedures for Extrapolating Creep Rupture Data – Conventional Method

Step 1: Plot the creep rupture data as log time to rupture versus log load level, as shown in Figure B.2-1. Do this for each temperature in which creep rupture data is available. For some materials, a semi-log rather than a log-log plot could be used. The plotting method that provides the best and most consistent fit of the data should be used. In general, approximately 12 to 18 data points (i.e., combined from all temperature levels tested to produce the envelope for a given product, with a minimum of 4 data points at each temperature) are required to establish a rupture envelope (Jewell and Greenwood, 1988; ASTM D2837). The data points should be evenly distributed through each log cycle of time. Rupture points with a time to rupture of less than 5 hours should in general not be used, unless it can be shown that these shorter duration points are consistent with the rest of the envelope (i.e., they do not contribute to non-linearity of the envelope). As a guide, three of the test results should have rupture times (not shifted by temperature acceleration) of 10 to 100 hours, four of the test results should have rupture times between 100 and 1,000 hours, and four of the test results should have rupture times of 1,000 to 10,000 hours, with at least one additional test result having a rupture time of approximately 10,000 hours (1.14 years) or more. It is recommended that creep strain be measured as well as time to rupture, since the creep strain data may assist with conventional time-temperature shifting and in identifying any change in behavior that could invalidate extrapolation of the results.

Step 2: Extrapolate the creep rupture data. Elevated temperature creep rupture data can be used to extrapolate the rupture envelope at the design temperature through the use of a time shift factor, a_T . If the rupture envelope is approximately linear as illustrated in Figure B.2-1(a), the single time shift factor a_T should be adequate to perform the time-temperature superposition.

Note 2: This time-temperature superposition procedure assumes that the creep-rupture curves at all temperatures are linear on a semi-logarithmic or double logarithmic scale and parallel. It has been found empirically that the curves for PET are semi-logarithmic and approximately parallel, or double logarithmic and approximately parallel in the case of HDPE and PP. It should be pointed out that the theory of Zhurkov (1965), 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 double logarithmic diagram, and that their gradients should be stress-dependent.

Use of a single time shift factor to shift all the creep rupture data at a given temperature, termed "block shifting," assumes that the shift factor a_T is not highly stress level dependent and that the envelopes at all temperatures are parallel, allowing an average value of a_T to be used for all of the rupture points at a given temperature. While research reported in the literature indicates that a_T may be somewhat stress level dependent and that the curves at all temperatures are not completely parallel, this assumption tends to result in a more conservative assessment of the creep reduction factor RF_{CR} (Thornton and Baker, 2002).

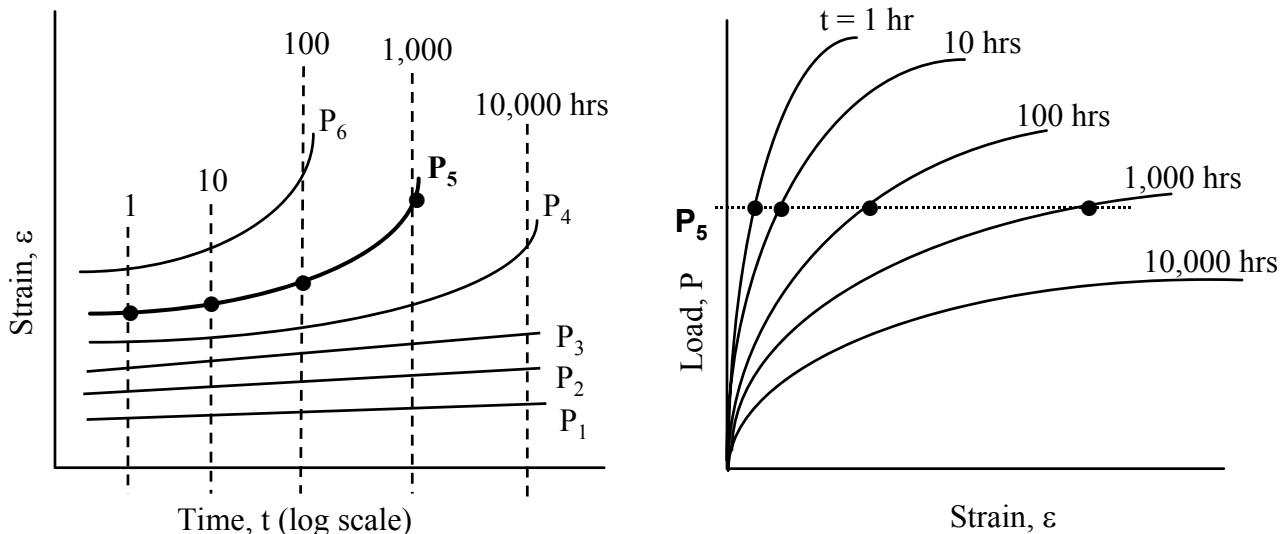


Figure B.2-1. Typical Stress Rupture Data for Geosynthetics, and the Determination of Shift Factors for Time-Temperature Superposition.

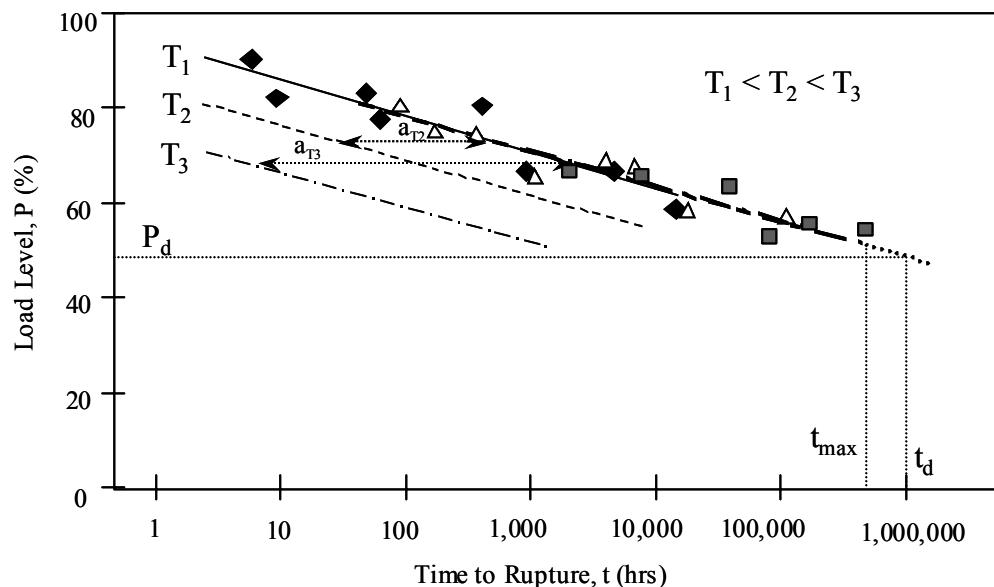


Figure B.2-2. Extrapolation of Stress Rupture Data and the Determination of the Creep Limit Load.

The time to rupture for the elevated temperature rupture data is shifted in accordance with the following equation:

$$t_{\text{amb}} = (t_{\text{elev}})(a_T) \quad (\text{B.2-1})$$

where, t_{amb} is the predicted time at the ambient or temperature to reach rupture under the specified load, t_{elev} is the measured time at elevated temperature to reach a rupture under the specified load, and a_T is the time shift factor. a_T can be approximately estimated using a visual/graphical approach as illustrated in figures B.2-1 and B.2-2. The preferred approach, however, is to use a computer spreadsheet optimization program to select the best shift factors for each constant temperature block of data to produce the highest R^2 value for the combined creep rupture envelope to produce the result in Figure B.2-2.

Note 3: *Incomplete tests may be included, with the test duration replacing the time to rupture, but should be listed as such in the reported results, provided that the test duration, after time shifting, is 10,000 hours or more. The rule for incomplete tests is as follows.*

The regression should be performed with and without the incomplete tests included. If the incomplete test results in an increase in the creep limit, keep the incomplete tests in the regression, but if not, do not include them in the regression, in both cases for incomplete tests that are 10,000 hours in duration after time shifting or more. Record the duration of the longest test which has ended in rupture, or the duration of the longest incomplete test whose duration exceeds its predicted time to failure: this duration is denoted as t_{max} .

It is preferred that creep rupture data be extrapolated statistically beyond the elevated temperature time shifted data using regression analysis (i.e., curve fitting) up to a maximum of one log cycle of time for all geosynthetic polymers (greater extrapolation using only statistical methods is feasible, but uncertainty in the result increases substantially and must be taken into account). Therefore, adequate elevated temperature data should be obtained to limit the amount of statistical extrapolation required.

Note 4: *There may be situations where extrapolation to create a creep rupture envelope at a lower temperature than was tested is necessary. Situations where this may occur include the need to elevate the ambient temperature to have greater control regarding the temperature variations during the creep testing (i.e., ambient laboratory temperature may vary too much), or for sites where the effective design temperature is significantly lower than the “standard” reference temperature used for creep testing (e.g., northern or high elevation climates). In such cases, it is feasible to use lower bound shift factors based on previous creep testing experience to allow the creep rupture envelope to be shifted to the lower temperature, as shift factors for the materials typically used for geosynthetic reinforcement are reasonably consistent. Based on previous creep testing experience and data reported in the literature (Chow and Van Laeken 1991; Thornton, et al. 1998; Thornton, et al. 1998a; Lothspeich and Thornton 2000; Takemura 1959; Bush, 1990; Popelar, et al. 1990; Wrigley, et al. 2000; Takaku 1980; Thornton and Baker 2000), shift factors for HDPE and PP geosynthetics are typically in the range of 0.05 to 0.18 decades (i.e., log cycles of time) per 1°C increase in temperature (i.e., a 10°C increase would result in a time shift factor of 12 to 15) and 0.05 to 0.12 decades per 1°C increase in temperature for PET geosynthetics. It is recommended that if shifting the creep rupture envelope to temperatures below the available data is necessary, that a shift factor of 0.05 decades per 1°C increase in temperature for PP, HDPE, and PET be used. This default shift factor should not be used to shift the creep rupture data more than 10°C .*

Step 3: Once the creep data has been extrapolated, determine the design, lot specific, creep limit load by taking the load level at the desired design life directly from the extrapolated stress rupture envelope as shown in Figure B.2-2. If statistical extrapolation beyond the time shifted stress rupture envelopes (PP or HDPE), or beyond the actual data if temperature accelerated creep data is not available, is necessary to reach the specified design life, the calculated creep load T_l should be reduced by an extrapolation uncertainty factor as follows:

$$T_l = P_{cl}/(1.2)^{x-1} \quad (\text{B.2-3})$$

where P_{cl} is the creep limit load taken directly from the extrapolated stress rupture envelope, and “x” is the number of log cycles of time the rupture envelope must be extrapolated beyond the actual or time shifted data, and is equal to $\log t_d - \log t_{max}$ as illustrated in Figure B.2-2. The factor $(1.2)^{x-1}$ is the extrapolation uncertainty factor. If extrapolating beyond the actual or time shifted data less than one log cycle, set “x-1” equal to “0”. This extrapolation uncertainty factor only applies to statistical extrapolation beyond the actual or time shifted data using regression analysis and assumes that a “knee” in the rupture envelope beyond the actual or time shifted data does not occur.

Note 5: A condition on the extrapolation is that there is no evidence or reason to believe that the rupture behavior will change over the desired design life. It should be checked that at long durations, and at elevated temperatures if used:

- There is no apparent change in the gradient of the creep-rupture curve
- There is no evidence of disproportionately lower strains to failure
- There is no significant change in the appearance of the fracture surface.

Any evidence of such changes, particularly in accelerated tests, should lead to the exclusion of any reading where either the gradient, strain at failure or appearance of the failure is different to those in the test with the longest failure duration. Particular attention is drawn to the behavior of unoriented thermoplastics under sustained load, where a transition in behavior is observed in long-term creep-rupture testing (i.e., the so called “ductile to brittle transition – Popelar, et al., 1991). The effect of this transition is that the gradient of the creep-rupture curve becomes steeper 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/FDIS 9080:2001, ASTM D2837, and Popelar, et al. (1991).

This extrapolation uncertainty factor also assumes that the data quality is good, data scatter is reasonable, and that approximately 12 to 18 data points which are well distributed (see Step 1 for a definition of well distributed) defines the stress rupture envelope for the product. If these assumptions are not true for the data in question, this uncertainty factor should be increased. The uncertainty factor may also need to be adjusted if a method other than the one presented in detail herein is used for extrapolation. This will depend on how well that method compares to the method provided in this appendix. This extrapolation uncertainty factor should be increased to as much as $(1.4)^x$ if there is the potential for a “knee” in the stress rupture envelope to occur beyond the actual or time shifted data, or

if the data quality, scatter, or amount is inadequate. Furthermore, if the data quantity or distribution over the time scale is inadequate, it may be necessary to begin applying the extrapolation uncertainty factor before the end of the time shifted data.

Note 6: Based on experience, the R^2 value for the composite (i.e., time shifted) creep rupture envelope should be approximately 0.8 to 0.9 or higher to be confident that Equation B.2-3 will adequately address the extrapolation uncertainty. If the R^2 value is less than approximately 0.6 to 0.7, extrapolation uncertainty is likely to be unacceptably high, and additional testing and investigation should be performed. In general, such low R^2 values are typically the result of data that is too bunched up, unusually high specimen to specimen variability, or possibly poor testing technique.

B.3 Procedures for Extrapolating Creep Rupture Data – Stepped Isothermal Method (SIM)

An alternative creep strain/rupture analysis and extrapolation approach that has recently become available for geosynthetics is the Stepped Isothermal Method (SIM) proposed, illustrated, and investigated by Thornton, et. al. (1997), Thornton, et. al. (1998), Thornton, et. al. (1998), and Thornton and Baker (2002). SIM has been applied successfully to PET geogrids and PP geotextiles. SIM utilizes an approach similar to the Williams-Landell-Ferry, or WLF, approach to creep extrapolation (Ferry, 1980), where master creep curves for a given material are produced from a series of short-term tests (i.e., creep test durations on the order of a few hours) on the same specimen over a wide range of temperatures (i.e., while the load on the specimen is held constant, the temperature is increased in steps). The sections of creep curve at the individual temperatures are shifted in time and combined to form a continuous prediction of the creep strain at the starting temperature.

Though the general principles of this method have been in use for many years in the polymer industry (Ferry, 1980), it has been only recently that this approach has been used for geosynthetics. Though this approach was initially developed to extrapolate creep strain data, it has been adapted to produce stress rupture data by taking the specimen to rupture once the highest test temperature is reached. In effect, through time shifting of the creep strain data obtained prior to rupture, the rupture point obtained has an equivalent shifted time that is several orders of magnitude greater than the actual test time, which could be on the order of only a few days.

The method is conducted in accordance with ASTM D 6992. Key issues are the very short test time used for this method, potential use of temperatures that are well above transitions in the geosynthetic material, and its complexity. Key technical advantages of the method, however, include more accurate determination of time shift factors, since the same specimen is used at the same load level at all of the temperatures (the “conventional” method must deal with the effect of specimen to specimen variability when determining the shift factors), and that time shift factors between temperatures are determined at the same load level, eliminating the effect of load level in the determination of the shift factors (in the “conventional” method, the shift factors used are in fact an average value for a wide range of loads).

SIM can be considered for use in generating and extrapolating geosynthetic creep and creep rupture data provided this method is shown to produce results which are consistent with the “conventional” extrapolation techniques recommended in this appendix. To this end, creep-rupture testing shall be conducted using conventional tests (ASTM D5262) and SIM

tests (ASTM D6992). At least six SIM rupture tests and six conventional rupture tests and shall be conducted one of the products in the product line being evaluated. Of the six SIM rupture tests, four shall have rupture times (shifted as appropriate) between 100 and 2000 hours and two shall have rupture times greater than 2000 hours. All of the conventional creep rupture points shall be obtained at the reference temperature (i.e., not temperature shifted). Creep rupture plots shall be constructed, regression lines computed and the log times to rupture determined at a load level that corresponds to 1,000 hours and 50,000 hours on the conventional creep rupture envelope, for the two data sets. The log time to rupture for the SIM regression at this load level shall be within the upper and lower 90% confidence limits of the mean conventional regressed rupture time at the same load level using Student's *t* test.

The confidence limit for the regression performed for the conventional creep rupture data is given by (Wadsworth, 1998):

$$\log t_L = \log t_{reg} \pm \left[t_{\alpha,n-2} \sqrt{\frac{1}{n} + \frac{(P - \bar{P})^2}{\sum (P_i - \bar{P})^2}} \right] \times \sigma \quad (\text{B.3-1})$$

and

$$\sigma = \sqrt{\frac{\sum [\log t_i - \bar{\log t}]^2 - \frac{\sum [(P_i - \bar{P})(\log t_i - \bar{\log t})]^2}{n-2}}{n-2}} \quad (\text{B.3-2})$$

where:

$\log t_L$ = lower and upper bound confidence limit. The + or - term in Equation B.2-1 results in the lower and upper bound confidence limits, respectively.

t_{reg} = time corresponding to the load level from the conventional creep rupture envelope at which the comparison between the two envelopes will be made (e.g., at 1,000 and 50,000 hrs after time shifting)

$t_{\alpha,n-2}$ = value of the *t* distribution determined from applicable Student *t* table (or from the Microsoft EXCEL function TINV($\alpha, n-2$)) at $\alpha = 0.10$ and $n-2$ degrees of freedom (this corresponds to the 90% two-sided prediction limit).

n = the number of rupture or allowable run-out points in the original test sample (i.e., the conventional creep rupture data)

P = load level obtained at t_{reg} from the regression line developed from the conventional creep rupture testing

\bar{P} = the mean rupture load level for the original test sample (i.e., all rupture or run-out points used in the regression to establish the conventional creep rupture envelope)

P_i = the rupture load level of the i 'th point for the rupture points used in the regression for establishing the conventional creep rupture envelope

$\log t$ = the mean of the log of rupture time for the original test sample (i.e., all rupture or run-out points used in the regression to establish the conventional creep rupture envelope)

t_i = the rupture time of the i 'th point for the rupture points used in the regression for establishing the conventional creep rupture envelope

Once $\log t_L$, both upper and lower bound, has been determined at the specified load level, compare these values to the log rupture time (i.e., $\log t_{SIM}$) obtained for the SIM creep rupture envelope test at the specified load level (e.g., 1,000 and 50,000 hours). The value of $\log t_{SIM}$ at the two specified load levels must be between the upper and lower bound confidence limits ($\log t_L$). If this requirement is not met, perform two additional SIM tests at each load level P for the specified t_{reg} where this comparison was made and develop a new SIM creep rupture envelope using all of the SIM data. If for the revised SIM regression envelope resulting from these additional tests this criterion is still not met, perform adequate additional conventional creep rupture testing to establish the complete rupture envelope for the product in accordance with this appendix).

If the criterion provided above is met, the SIM testing shall be considered to be consistent with the conventional data, and SIM may be used in combination with the conventional data to meet the requirements of Section B.2 regarding the number of rupture points and their distribution in time and maximum duration. Therefore, the combined data can be used to create the creep rupture envelope as shown in Figure B.2-2. In that figure, the SIM data shall be considered to already be time shifted. Equation B.2-3 is then used to determine T_1 .

B.4 Determination of RF_{CR}

The creep reduction factor, RF_{CR} , is determined by comparing the long-term creep strength, T_1 , to the ultimate tensile strength (ASTM D4595 or ASTM D6637) of the sample tested for creep (T_{lot}). The sample tested for ultimate tensile strength should be taken from the same lot, and preferably the same roll, of material that is used for the creep testing. For ultimate limit state design, the strength reduction factor to prevent long-term creep rupture is determined as follows:

$$T_{al} = \frac{P_{95}}{RF_{ID} \times RF_D} \quad (B.4-1)$$

where, T_{lot} is the average lot specific ultimate tensile strength (ASTM D4595 or ASTM D6637) for the lot of material used for the creep testing. Note that this creep reduction factor takes extrapolation uncertainty into account, but does not take into account variability in the strength of the material. Material strength variability is taken into account when RF_{CR} , along with RF_{ID} and RF_D , are applied to T_{ult} to determine the long-term allowable tensile strength, as T_{ult} is a minimum average roll value. The minimum average roll value is essentially the value that is two standard deviations below the average value.

B.5 Use of Creep Data from “Similar” Products and Evaluation of Product Lines

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 or both of the following conditions are met:

- The chemical and physical characteristics of tested products and proposed products are shown to be similar. Research data, though not necessarily developed by the product manufacturer, 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.
- A limited testing program is conducted on the new or similar product in question and compared with the results of the previously conducted full testing program.

For polyolefins, similarity could be judged based on molecular weight and structure of the main polymer (i.e., is the polymer branched or crosslinked, is it a homopolymer or a blend, percent crystallinity, etc.), percentage of material reprocessed, tenacity of the fibers and processing history, and polymer additives used (i.e., type and quantity of antioxidants or other additives used). For polyesters and polyamides, similarity could be judged based on molecular weight or intrinsic viscosity of the main polymer, carboxyl end group content, percent crystallinity, or other molecular structure variables, tenacity of the fibers and processing history, percentage of material reprocessed or recycled, and polymer additives used (e.g., pigments, etc.). The untested products should also have a similar macrostructure (i.e., woven, nonwoven, extruded grid, needlepunched, yarn structure, etc.) and fiber dimensions (e.g., thickness) relative to the tested products. It should be noted that percent crystallinity is not a controlled property and there is presently no indication of what an acceptable value for percent crystallinity should be.

For creep evaluation of a similar product not part of the original product line, this limited testing program should include creep tests taken to at least 1,000 to 2,000 hours in length before time shifting if using the “conventional” creep testing approach, with adequate elevated temperature data to permit extrapolation to 50,000 hours or more. If it has been verified that SIM can be used, in accordance with Section B.3, durations after time shifting due to elevated temperature up to a minimum of 50,000 hours are required. A minimum of 4 data points per temperature level tested should be obtained to determine time shift factors and to establish the envelope for the similar product. These limited creep test results must show that the performance of the similar product is equal to or better than the performance of the product previously tested. This comparison must demonstrate that there is no statistical difference between the old product regression line and the regression line obtained for the similar product at a time of 2,000 hours (not temperature accelerated) and 50,000 hours (after time shifting) using a student-t distribution at a confidence level of 0.10 (see Equation B.3-1). If no statistical difference is observed, the results from the full testing program on the older or similar product could be used for the new/similar product. If this is not the case, then a full testing and evaluation program for the similar product should be conducted.

Similarly, for extension of the creep data obtained on one product in the product line (i.e., the primary product tested, which is typically a product in the middle of the range of products in the product line) to the entire product line as defined herein, a limited creep testing program must be conducted on at least two additional products in the product line. The combination of the three or more products must span the full range of the product line in terms of weight and/or strength. The limited test program described in the preceding paragraph should be applied to each additional product in the product line. The loads obtained for the data in each envelope should then be normalized by the lot specific ultimate tensile strength, T_{lot} . All three envelopes should plot on top of one another, once normalized in this manner, and the two additional product envelopes should be located within the confidence limits for the product with the more fully developed creep rupture envelope (i.e., the “primary” product) as described above for “similar” products. If this is the case, then the creep reduction factor for the product line shall be the lesser of the reduction factor obtained for the product with the fully developed rupture envelope and the envelope of all three products combined, and normalization using the ultimate tensile strength shall be considered acceptably accurate.

If this is not the case, then the creep rupture envelopes for the other two products, plus enough other products within the product line, to establish the trend in RF_{CR} as a function of product weight or ultimate tensile strength, so that the RF_{CR} for the other products within the product line can be accurately interpolated. Furthermore, T_{al} must be determined in accordance with Note 7.

Note 7: *Note that normalization using the ultimate lot specific tensile strength may not be completely accurate for some geosynthetic products regarding characterization of creep rupture behavior; and other normalization techniques may be needed (Wrigley, et al., 1999). In such cases, individual creep reduction factors for each product in the product line may need to be established through fully developed creep rupture envelopes for representative products obtained at the low, middle, and high strength end of the product series. Once the creep limited strength, P_{cl} and the creep reduction factors are established for each product, in this case, product variability must still be taken into account. In such cases, T_{al} must be the lesser of the determination from Equation 1 and the following determination:*

$$T_{al} = \frac{P_{95}}{RF_{ID} \times RF_D}$$

where,

P_{95} = the tensile strength determined from the 95% lower bound prediction limit for the creep rupture envelope at the specified design life (see Equations 4 and 5 in “Quality Assurance (QA) Criteria for Comparison to Initial Product Acceptance Test Results”)

References

- AASHTO, 2002, *Standard Specifications for Highway Bridges*, American Association of State Highway and Transportation Officials, Seventeenth Edition, Washington, D.C., USA, 686 p.
- Andrawes, K. Z., McGown, A., and Murray, R. T., 1986, "The Load-Strain-Time Behavior of Geotextiles and Geogrids," *Proceedings of the Third International Conference on Geotextiles*, Vienna, Austria, pp. 707-712.
- Bush, D.I., 1990, "Variation of Long-Term Design Strength of Geosynthetics in Temperatures up to 40°C", *Proceedings of the Fourth International Conference on Geotextiles, Geomembranes, and Related Products*, The Hague, Netherlands, pp. 673-676.
- Chow and Van Laeken 1991*, "Viscoelastic Relaxation in oriented Semicrystalline Polymers," *Polymer*, Vol. 32, pp. 1798-1802.
- den Hoedt, G., Voskamp, W., van den Heuvel, C. J. M., 1994, "Creep and Time-to-Rupture of Polyester Geogrids at Elevated Temperatures," *Proceedings of the Fifth International Conference on Geotextiles, Geomembranes, and Related Products*, Singapore, pp. 1125-1130.
- Ferry, J. D., 1980, *Viscoelastic Properties of Polymers*, 3rd Edition, John Wiley and Sons, NY.
- Findley, W. N., Lai, J. S., Onaran, K., 1976, *Creep and Relaxation of Nonlinear Viscoelastic Materials*, Dover Publications, NY, 369 pp.
- Helwany, B., Wu, J. T. H., 1992, "A Generalized Creep Model for Geosynthetics," *International Symposium on Earth Reinforcement Practice*, Japan, pp.
- Jewell, R.A. and Greenwood, J.H., 1988, "Long-Term Strength and Safety in Steep Soil Slopes Reinforced by Polymer Materials", *Geotextiles and Geomembranes*, Vol. 7, Nos. 1 and 2, pp. 81-118.
- Koerner, R. M., 1990, "Determination of the Long-Term Design Strength of Stiff Geogrids," GRI Standard Practice GG4(a).
- Lothspeich, S., and Thornton, S., 2000, "Comparison of Long-term Design Reduction Factors Based on Creep Rupture and Creep Strength Criteria for Several Geosynthetic Reinforcing Materials," *EuroGeo 2*, pp. 341-346.
- McGown, A., Paine, N., and DuBois, D.D., 1984, "Use of Geogrid Properties in Limit Equilibrium Analysis", *Proceedings of the Symposium on Polymer Grid Reinforcement in Civil Engineering*, Paper No. 1.4, pp. 1-5.
- Murray, R. T., McGown, A., 1988, "Assessment of the Time Dependent Behavior of Geotextiles for Reinforced Soil Applications," *Durability of Geotextiles RILEM*, Chapman and Hall.
- Popelar, et al., 1990, "Viscoelastic Material Characterization and Modeling for Polyethylene," *Polymer Engineering and Science*, Vol. 30, no. 10, pp. 577-586.

- Popelar, C.H., Kenner, V.H., and Wooster, J.P., 1991, "An Accelerated Method for Establishing the Long Term Performance of Polyethylene Gas Pipe Materials", *Polymer Engineering and Science*, Vol. 31, pp. 1693-1700.
- Takaku, A., 1981, "Effect of Drawing on Creep Fracture of Polypropylene Fibers", *Journal of Applied Polymer Science*, Vol. 26, pp. 3565-3573.
- Takemura, 1959, Theoretical Consideration of the Effect of Crystallinity on the Viscoelastic Properties of Polyethylene," *Journal of Applied Polymer Science*, Vol. 38, pp. 471-478.
- Thornton, J. S., Allen, S. R., and Thomas, R. W., (1997) "Approaches for the Prediction of Long Term Viscoelastic Properties of Geosynthetics from ShortTerm Tests," *Geosynthetics '97*, IFAI, Long Beach, CA, Vol. 1, pp. 277-291.
- Thornton, J. S., Allen, S. R., Thomas, R. W., and Sandri, D., 1998, "The Stepped Isothermal Method for Time-Temperature Superposition and Its Application to Creep Data of Polyester Yarns," *Sixth International Conference on Geotextiles, Geomembranes, and Related Products*, Atlanta, GA, pp.699-706.
- Thornton, J. S., and Baker, T. L., 2002, "Comparison of SIM and conventional Methods for Determining Creep-Rupture Behavior of a Polypropylene Geotextile," *7th International Geosynthetics Conference*, Nice, France, Vol. 4, pp. 1545-1550.
- Thornton, J. S., Paulson, J., and Sandri, D., 1998a, "Conventional and Stepped Isothermal Methods for Characterizing Long-Term Creep Strength of Polyester Geogrids," *Sixth International Conference on Geotextiles, Geomembranes, and Related Products*, Atlanta, GA, pp.691-698.
- Wadsworth, H., 1998, *Handbook of Statistical Methods for Engineers and Scientists*, McGraw-Hill, 688 pp.
- Wilding, M.A. and Ward, I.M., 1978, "Tensile and Creep Recovery in Ultra-High Modulus Polyethylenes," *Polymer*, Vol. 19, pp.
- Wilding, M.A. and Ward, I.M., 1981, "Creep and Recovery of Ultra High Modulus Polyethylene", *Polymer*, Vol. 22, pp. 870-876.
- Wrigley, N. E., Austin, R. A., and Harrison, P. E., 1999, "The Long-Term Strength of Geogrid Reinforcement," *Geosynthetics '99*, Boston, MA, USA, Vol. 2, pp. 711-721.
- Zhurkov, S. N., 1965, "Kenetic Concept of the Strength of Solids," *International Journal of Fracture Mechanics*, Vol. 1, pp. 311-323.

WSDOT Test Method No. 925, Appendix C

Strain Based Creep Testing and Extrapolation

This appendix provides supplementary information to Appendix B regarding the use and extrapolation of creep strain data.

As is true for stress rupture testing, in-air long-term laboratory creep tests should be conducted for a range of load levels in accordance with ASTM D5262, adequate for extrapolation to the required design life as described in this appendix. Specimens should be tested in the direction in which the load will be applied in use. Full width specimens should be tested, unless it can be shown through a limited testing program that single rib, yarn, or narrow width specimens can be used without affecting the creep rupture envelope (see beginning of Appendix B), though in the case of creep strain testing and extrapolation, the rupture envelope is defined as the time to reach the instability limit strain (described later in Appendix C). Test results should be extrapolated to the required structure design life. Based on the extrapolated test results, for ultimate limit state design, determine the highest load level, designated T_1 , at which the log time creep rate continues to decrease with time and which precludes both ductile and brittle creep rupture within the required lifetime. T_1 should be determined at the required design life and at the effective design site temperature. Unless otherwise specified or required by site specific temperature data, an effective design temperature of 20° C (T_{amb}) should be assumed.

As stated above, the application of the extrapolated creep data as described in this appendix is to estimate the highest load level within the specified design lifetime that precludes creep rupture. When using creep strain data, creep rupture is assumed to occur, or is at least eminent, when the strain exceeds the instability strain limit (see Section C.1). Creep strain data can be used for other purposes, such as to estimate long-term deformations or to estimate long-term stiffness values. The extrapolated creep strain data developed in accordance with this Appendix can be used for these purposes as well.

C.1 Creep Strain Assessment Tools and Concepts

Creep strain curves are typically plotted as a function of time or the logarithm of time. In general, there are up to three stages of creep observed in polymeric materials – these include primary, secondary or steady-state, and tertiary creep. Primary creep strains are characteristically linear when plotted against a logarithmic time scale and increase at a decreasing rate on an arithmetic time scale. Secondary creep strains are typically linear when plotted against an arithmetic time scale. Tertiary creep is the rupture phase of creep and is characterized by a rapidly increasing creep rate with time. Geosynthetic structure tends to dominate primary creep (at least for nonwoven geotextiles, but much less so for woven geotextiles and not at all for geogrids), and the polymer characteristics tend to dominate secondary and tertiary creep mechanisms (Allen 1991). Polyolefins (HDPE and PP) tend to exhibit all three stages of creep, depending on the load level, whereas PET tends to only exhibit primary and tertiary creep. Figure C.1-1 illustrates these concepts.

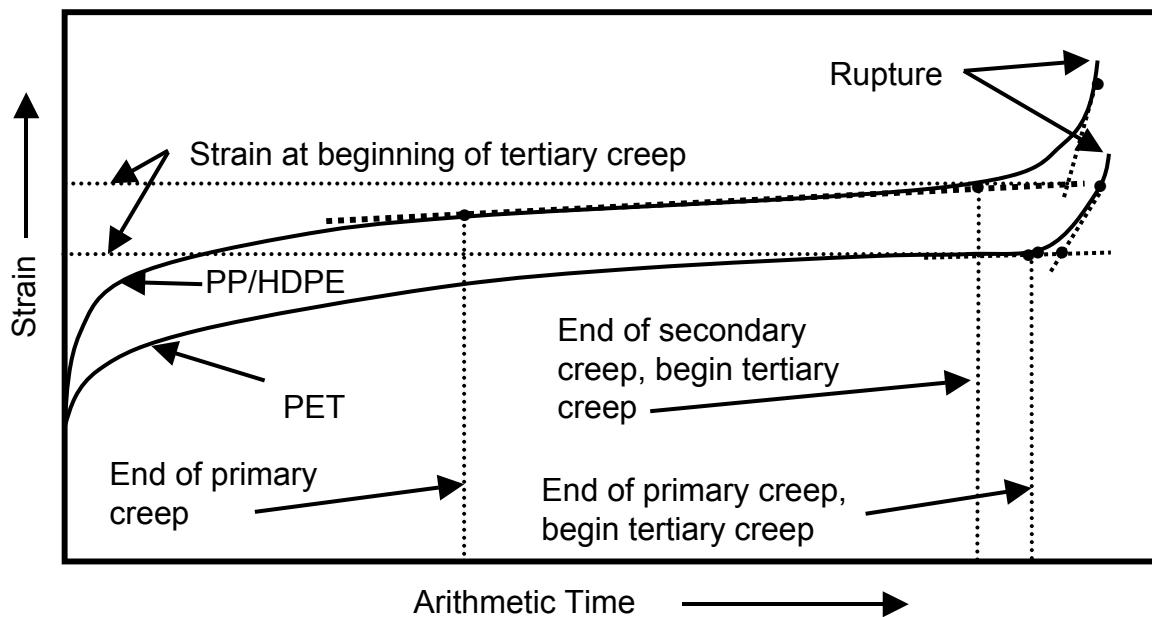
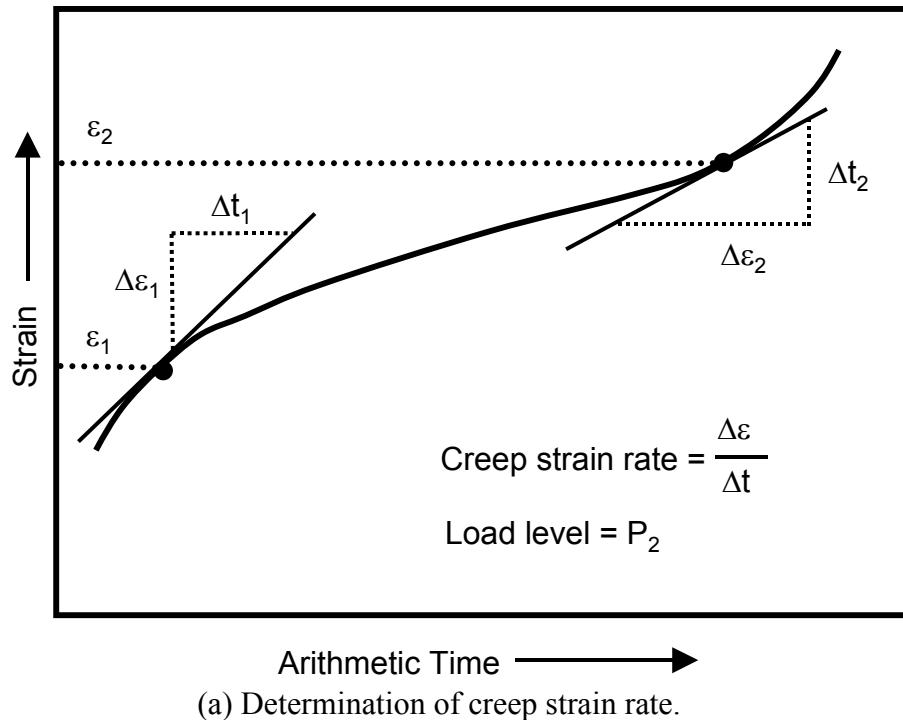


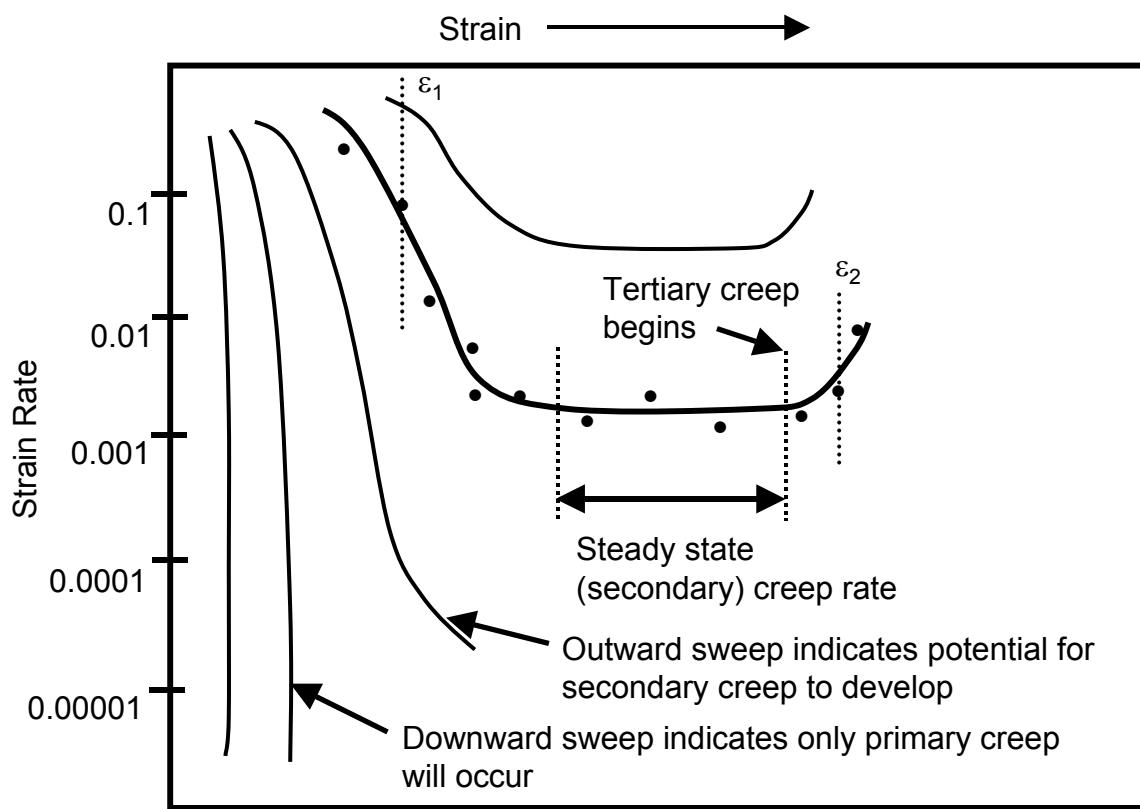
Figure C.1-1. Conceptual illustration of creep strain behavior, and the determination of the strain at the beginning of tertiary creep from creep strain data.

The instability limit strain is defined as the strain beyond which the material exhibits signs of instability, i.e., approaches failure (Andrawes, et. al., 1986). When extrapolating creep strain data, it is important to not extrapolate the data to strain levels that are in excess of the instability limit strain, as doing so would produce invalid results. The determination of this limit strain can be the most difficult part of assessing the creep rupture limit from creep strain data. The actual rupture strain, which occurs at the end of tertiary creep, for a given material at a given load level is difficult to measure as well as to identify. A more consistent and more easily measured instability limit strain would be the strain level where tertiary creep begins as illustrated in Figure C.1-1. However, if rupture occurs during the primary or secondary creep stage (e.g., PET) the instability limit strain is the rupture strain.

Another tool that can be useful in determining the strain at the beginning of tertiary creep is the Sherby-Dorn plot, as illustrated in Figure C.1-2. A Sherby-Dorn plot is a well known plotting technique used in polymer science (McGown et al. 1984a). Each curve represents a specific geosynthetic layer in a wall or a specific geosynthetic specimen tested at a specific load level. Creep strain rates observed under constant load are plotted against the total strain in the specimen or layer measured at the time the creep strain rate was calculated. The creep strain rate is simply the slope of the creep strain curve at a given point in time (see Figure C.1-2a). Curves that are linear or concave downward indicate that only primary creep is occurring, and that stabilization (no rupture) is likely. Curves that are concave upward indicate secondary or tertiary creep is occurring, and that rupture is likely. The closer the curves are located to the bottom left corner of the plot (Figure C.1-2), the better the creep performance of the material. The closer the curves are to the upper right corner, the more likely creep rupture will occur.



(a) Determination of creep strain rate.



(b) Interpretation of Sherby-Dorn plots.

Figure C.1-2. Development and Use of Sherby-Dorn Plots to Analyze Creep Strain Data.

Note that some interpretation of the creep curves through curve fitting is required to determine strain rates, since local jumps in the measured creep strain curves can cause wide variations in calculated creep strain rates. The jumps in the curves are typically the result of the short increments of time used in the calculations and the small magnitude of changes in strain readings that may be at the limit of the resolution of the measuring devices. Hence, the slope of the measured creep curves must be taken over fairly long increments of time to be meaningful.

Tertiary creep begins where the creep strain rate (based on an arithmetic time scale) begins to increase. The strain at the beginning of tertiary creep is located where the creep strain rate begins to increase after reaching a minimum value, at least for polyolefin geosynthetics. A minimum and then an increasing creep strain rate is very difficult to see for polyester geosynthetics on this type of plot. Therefore, Sherby-Dorn plots tend to not be very useful for polyester geosynthetics.

To determine the long-term instability limit strain, the measured creep strain and time near creep rupture (i.e., at the beginning of tertiary creep) for various load levels must be obtained. These strains are plotted versus time to the beginning of tertiary creep (the rupture phase) on a semi-log plot (i.e., log time), or possibly a log-log plot, to establish the trend in the data. In general, strains near rupture for times to the rupture phase from 10 hours up to approximately 10,000 hours should be obtained so that the data need only be extrapolated two log cycles of time or less. A minimum of one data point per log cycle of time should be obtained to define the trend, but more data points are likely to be needed to establish the trend.

Typical near rupture strain trends for various geosynthetic polymers are illustrated in Figure C.1-3. Strain near rupture which increases as time to the rupture phase increases may be indicative of ductile behavior, whereas strain near rupture which decreases as time to the rupture phase increases may be indicative of brittle behavior (i.e., localized crack growth). If ductile behavior is observed, a transition to brittle behavior is possible. If such a shift to brittle behavior occurred, the strain near rupture increase occurring as time to the rupture phase increases (ductile behavior) could be lost as behavior becomes more brittle. Until more is known, it is recommended that strains near rupture which appear to be increasing as time to the rupture phase increases not be depended upon when assessing the long-term instability limit strain. Therefore, if the strain near rupture increases as time to the rupture phase increases, which appears to be typical of polypropylene (PP) geosynthetics (Takaku, 1981; Allen, 1991, Thornton and Baker, 2002), the short-term (i.e., rupture times on the order of 10 hours) strain near rupture should be used as the instability limit strain. If the strain near rupture decreases as time to the rupture phase increases, which appears to be typical of high density polyethylene (HDPE) geosynthetics (Ingold, et. al., 1994; Allen and Bathurst, 1996) and polyester (PET) geosynthetics (Krumm, 1988; Allen and Bathurst, 1996), extrapolate (up to a maximum of two log cycles) to the strain near rupture at the specified design life using visual extrapolation, regression analysis, or time-temperature superposition if elevated temperature data is available, and reduce that strain by a reduction factor of 1.1 to account for potential uncertainty. This reduction factor could be adjusted depending on the amount and quality of the strain near rupture data. The determination of the long-term instability strain limit is conceptually illustrated in Figure C.1-3.

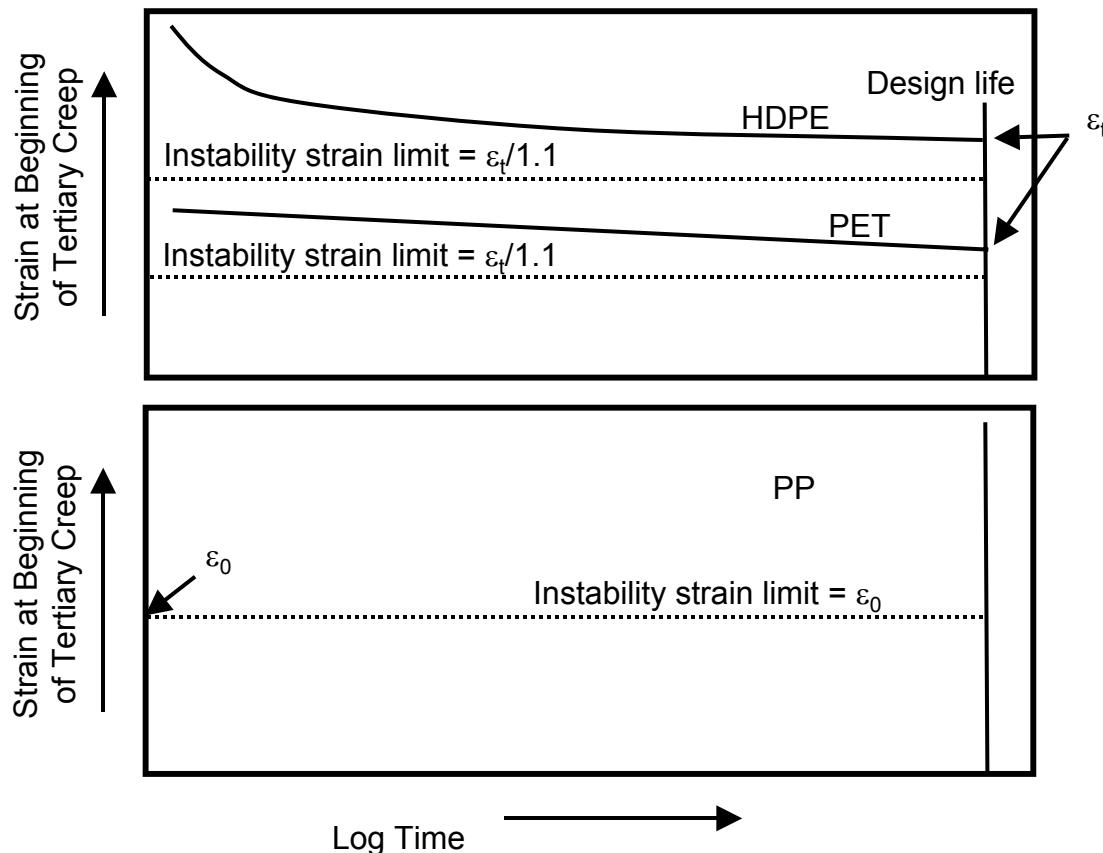


Figure C.1-3. Typical Near Rupture Behavior for Various Geosynthetic Polymers in Terms of Measured Strain.

If inadequate data is available to extrapolate measured strains near rupture to the long-term strain near rupture and the material type is likely to have strains near rupture which decrease with increasing time to the rupture phase (e.g., HDPE and PET), an acceptable alternative to estimate the instability limit strain is to take the peak strain measured from a wide width load-strain test (ASTM D4595 or ASTM D6637) and reduce it by a factor of 2.0.

Another tool that is useful for characterizing and working with creep strain data is the isochronous curve. Each isochronous (i.e., constant time) curve is created by taking load and strain levels from each creep curve at a given constant time and plotting them to form an isochronous curve. Some curve fitting may be necessary to account for specimen variability and to create a reasonably smooth curve. For HDPE, this curve fitting is reasonably straight-forward to do. However, for PET, the isochronous curves characteristically have an "s" shape at low strains resulting from load and strain dependent changes in the crystalline and between crystal arrangement of molecules within the polymer (Jewell and Greenwood, 1988; den Hoedt, et al, 1994). PP geosynthetics may also have inherent abrupt non-linearities in their isochronous curves at certain strain or load levels as observed by McGown, et al. (1984). Such changes in the curves resulting from physical processes in the polymer must be considered when constructing isochronous from creep strain data. Note that isochronous curves are not an extrapolation tool, but instead

are an interpolation tool. Isochronous curves provide a convenient method of interpolating between creep curves, which will be necessary to accomplish the creep extrapolation steps that follow.

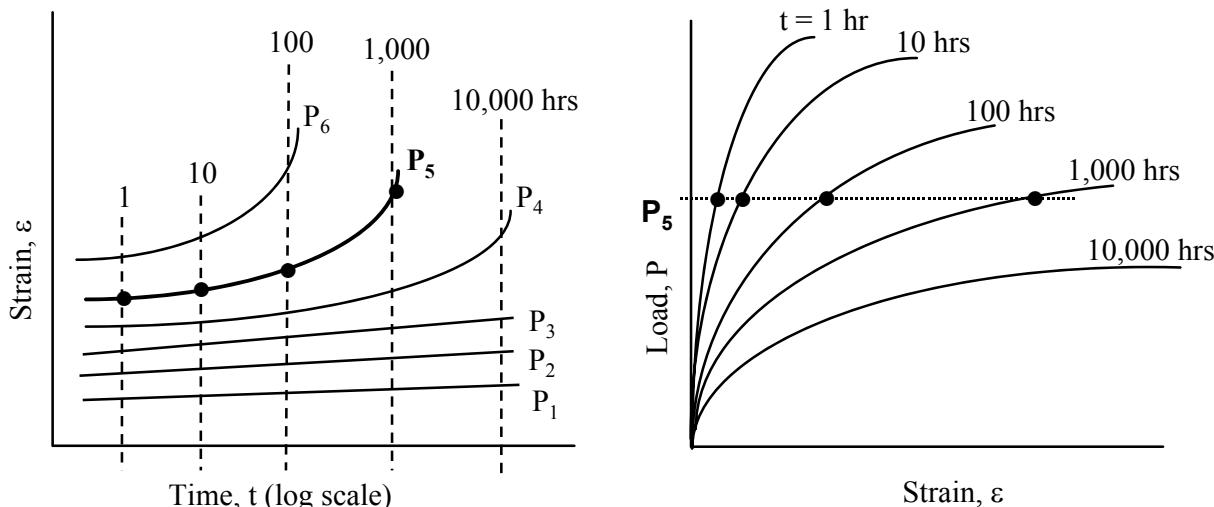


Figure C.1-4. Development of Isochronous Load-Strain Curves.

Creep stiffness curves as a function of time are also very useful to use for extrapolation purposes, or to simply estimate the long-term stiffness of the reinforcement for purposes of estimating deformation behavior. Select a constant strain or a constant load level from which to calculate the creep stiffness from the isochronous creep curves. At each point where the selected strain or load level intersects an isochronous curve, calculate the creep stiffness, J , as shown in Figure C.1-5, using the general form of the equation shown below:

$$J = P/\varepsilon \quad (\text{C.1-1})$$

where, “P” is the load, and “ ε ” is the strain. Each isochronous curve represents the specific time associated with the calculated creep stiffness. The creep stiffness values calculated should be plotted as a function of log time as shown in Figure C.1-5. Note that creep stiffness values can be calculated directly from the creep curves (Figure C.1-1) by identifying where the specified strain intersects each creep curve, or for each creep curve estimate the strain at each selected time. As shown in Figure C.2.1-1, the load or strain level at which the creep stiffness values are calculated should be selected such that the strain near the end of the specified design life is approximately equal to or less than the instability limit strain, if it is desired to predict the maximum load level that will preclude rupture, T_1 . Note that other strain or load levels could be selected to calculate the creep stiffness curves if it is desired to estimate deformations at working stress conditions or to estimate the long-term creep stiffness at working strains.

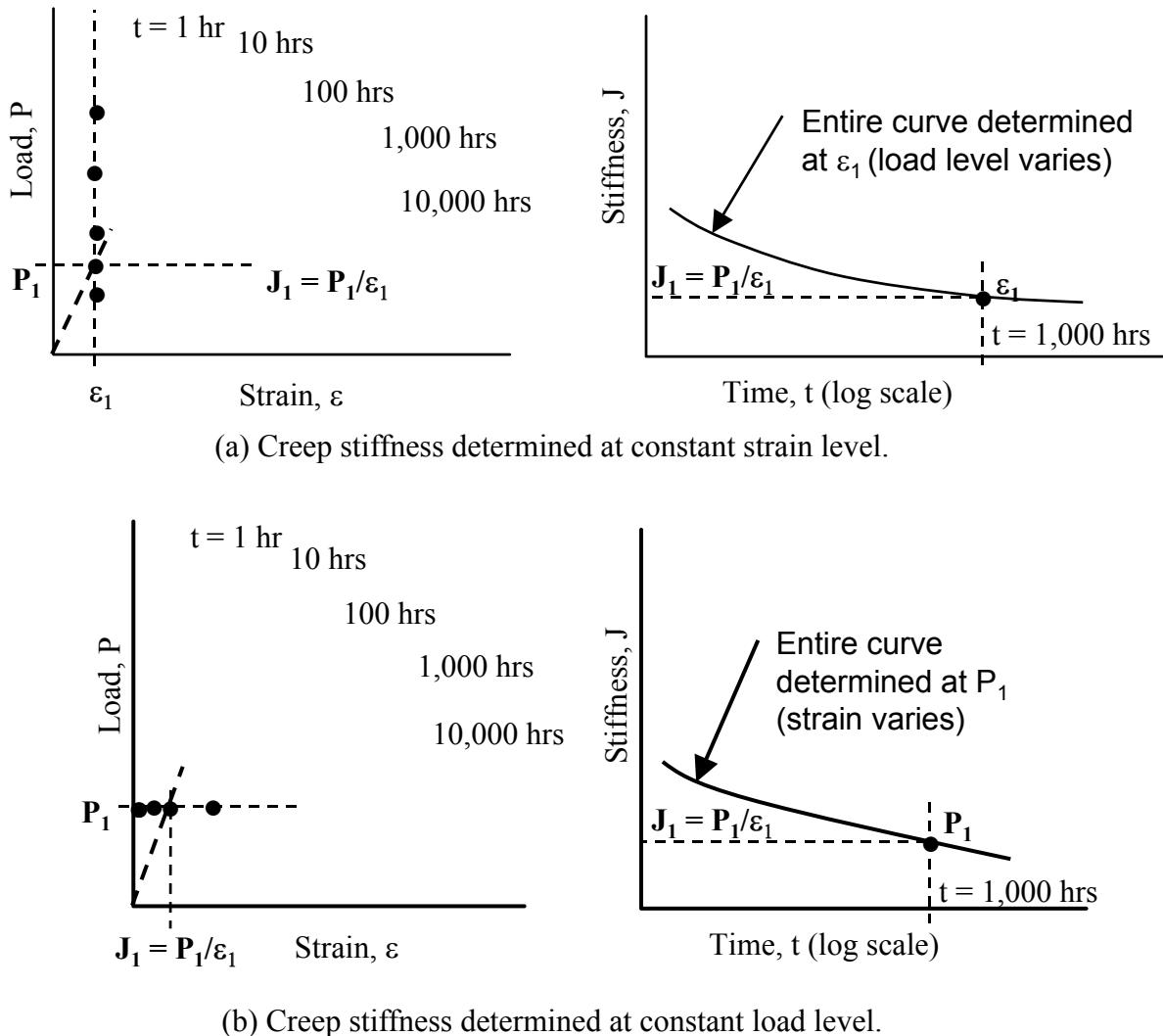


Figure C.1-5. Development of Creep Stiffness Curves.

C.2 Creep Strain Data Extrapolation

The ability to accelerate creep with temperature for polyolefins such as polypropylene (PP) or high density polyethylene (HDPE) has been relatively well defined (Takaku, 1981; Bush, 1990; Popelar, et. al., 1991). Since the focus of the creep strain extrapolation method provided in this appendix is on the creep limit to prevent rupture during the design lifetime required, the issues affecting creep rupture data extrapolation also affect creep strain data extrapolation. Therefore, as is true for creep rupture testing, temperature accelerated creep data is strongly recommended for polyolefins. For polyester (PET) geosynthetics, evidence indicates that temperature can also be used to accelerate PET creep, based on data provided by den Hoedt, et. al., (1994), and others.

If elevated temperature is used to obtain accelerated creep data, it is recommended that minimum increments of 10°C be used to select temperatures for elevated temperature creep testing. The highest temperature tested, however, should be below any transitions for the polymer in question. If one uses test temperatures below 70 to 75°C for polypropylene

(PP), high density polyethylene (HDPE), and PET geosynthetics, significant polymer transitions will be avoided. One should also keep in mind that at these high temperatures, significant chemical interactions with the surrounding environment are possible, necessitating that somewhat lower temperatures or appropriate environmental controls be used. These chemical interactions are likely to cause the creep test results to be conservative. Therefore, from the user's point of view, potential for chemical interactions is not detrimental to the validity of the data for predicting creep limits. However, exposure to temperatures near the upper end of these ranges could affect the stress-strain behavior of the material due to loss of molecular orientation, or possibly other effects that are not the result of chemical degradation. Therefore, care needs to be exercised when interpreting results from tests performed at temperatures near the maximum test temperatures indicated above. In general, if the stiffness of the material after exposure to the environment is significantly different from that of the virgin material, the stress-strain properties, and possibly the strength, of the material may have been affected by the exposure temperature in addition to the chemical environment. If the stiffness has been affected, the cause of the stiffness change should be thoroughly investigated to determine whether or not the change in stiffness is partially or fully due to the effect of temperature, or alternatively not use the data obtained at and above the temperature where the stiffness was affected.

A number of extrapolation and creep modeling methods have been reported in the literature (Findley, et. al., 1976; Wilding and Ward, 1978; Wilding and Ward, 1981; Takaku, 1981; McGown, et. al., 1984a; Andrawes, et. al., 1986; Murray and McGown, 1988; Bush, 1990; Popelar, et. al., 1991; Helwany and Wu, 1992). Many of the methods discussed in the literature are quite involved and mathematically complex.

Two creep extrapolation techniques are provided herein for creep rupture evaluation: the conventional method, which utilizes a simplified visual/graphical approach, temperature acceleration of creep, regression techniques, and statistical extrapolation, and the Stepped Isothermal Method (SIM). This does not mean that the more complex mathematical modeling techniques cannot be used to extrapolate creep of geosynthetics; they are simply not explained herein.

The two techniques identified above are described in more detail in Appendix B, and as follows:

C.2.1 Step-By-Step Procedures for Extrapolating Creep Strain Data – Conventional Method

Step 1: Plot the creep data. Plot the data as a semilog plot (log of time) or as an arithmetic plot (time). Do this separately for each temperature if data at elevated temperatures is available. For examples, see Figure C.1-1.

Step 2: Determine the instability limit strain (see Section C.1).

Step 3: Construct isochronous curves, as shown in Figure C.1-4.

Step 4: Develop creep stiffness curves for each temperature in which creep data is available, all at the same load level or strain level (see Figure C.1-5). Develop these stiffness curves at a strain level near the instability strain limit, or at a load level that results in a strain near the end of the specified design life that is approximately equal to the instability strain limit. These creep stiffness curves can then be used to perform time-

temperature superposition for the purpose of creep extrapolation. Note that more accurate time-temperature shift factors are likely to be obtained if the creep stiffness curves are produced at a constant load level (Figure C.1-5b) rather than constant strain level (Figure C.1-5a), as doing so avoids the additional uncertainty caused by the stress level dependence of the shift factors. In fact, using constant load level creep stiffness curves to determine shift factors should produce nearly identical results to the Stepped Isothermal Method (SIM), except that specimen to specimen variability will still be present (SIM eliminates the specimen to specimen variability when determining shift factors, since only one specimen is used – See Appendix B for more information on SIM).

Step 5: Extrapolate the creep data. For all geosynthetics, creep strain or stiffness data can be extrapolated statistically using regression analysis (i.e., curve fitting), or creep data can be accelerated by temperature to allow extrapolation using time-temperature superposition principles. It is well known that temperature accelerates many chemical and physical processes in a predictable manner. In the case of creep, this means that the creep strains under a given applied load at a relatively high temperature and relatively short times will be approximately the same as the creep strains observed under the same applied load at a relatively low temperature and relatively long times. This means that the time to a given creep strain or stiffness measured at an elevated temperature can be made equivalent to the time expected to reach a given creep strain or stiffness at in-situ temperature through the use of a time shift factor. Therefore, elevated temperature creep strain or stiffness data is made into equivalent in-situ temperature data as follows:

$$t_{amb} = (t_{elev})(a_T) \quad (C.2.1-1)$$

where, t_{amb} is the predicted time at in-situ temperature to reach a specified creep stiffness or strain under the specified load, t_{elev} is the measured time at elevated temperature to reach a specified creep stiffness or strain under the specified load, and a_T is the time shift factor. For example, this means that if the time to reach a creep stiffness J_{cl} at elevated temperature is 10,000 hours, the creep stiffness will also be J_{cl} at in-situ temperature at a time of (10,000) (a_T) hours. In this way, the creep stiffness curve at in-situ temperature can be extrapolated to longer times.

The magnitude of the time shift factor can be determined graphically as illustrated in Figure C.2.1-1, or regression analysis of the composite creep stiffness curve can be used to optimize the shift factors to produce the highest R^2 value for all of the time shifted data. Adjust a_T such that the creep stiffness curves at elevated temperature line up with the creep stiffness curve at the design (in-situ) temperature. Note that the magnitude of the shift factors for a given product can be different at different stages of creep (i.e., primary, secondary, or tertiary creep) and different load levels (see Appendix B). This should be considered when determining shift factors. See Note 4 in Appendix B, Section B.2 for additional considerations regarding the use of time shift factors.

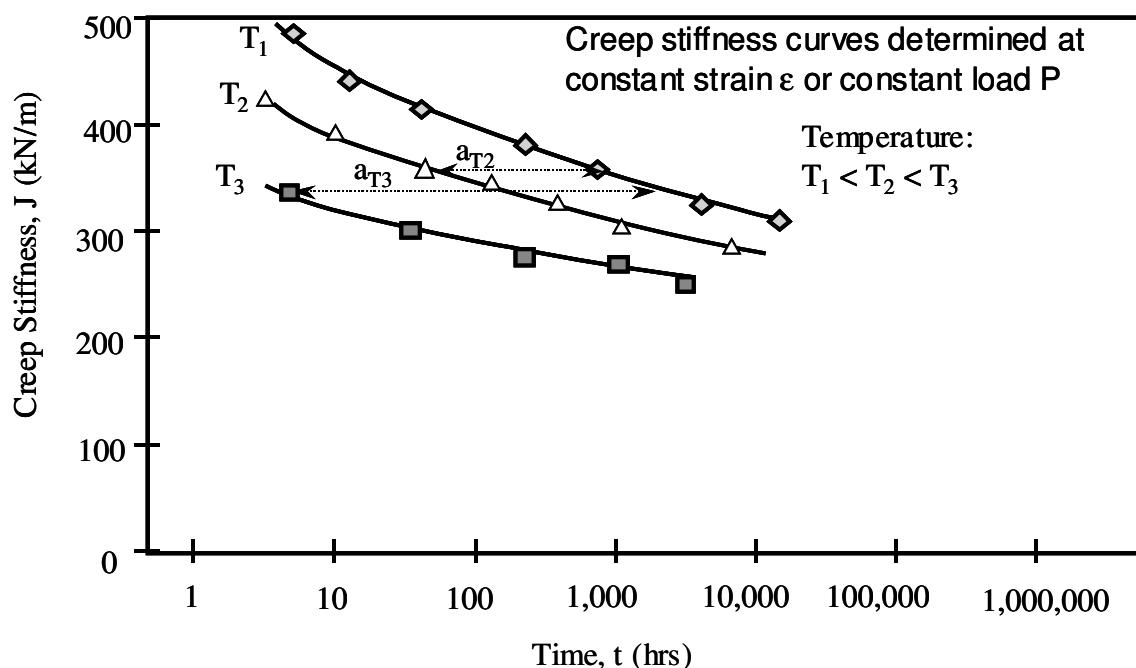
Step 6: Once the creep data has been extrapolated, determine the design, lot specific, creep limit load as follows:

$$T_l = (J_{cl})(\varepsilon_l) \quad (C.2.1-2)$$

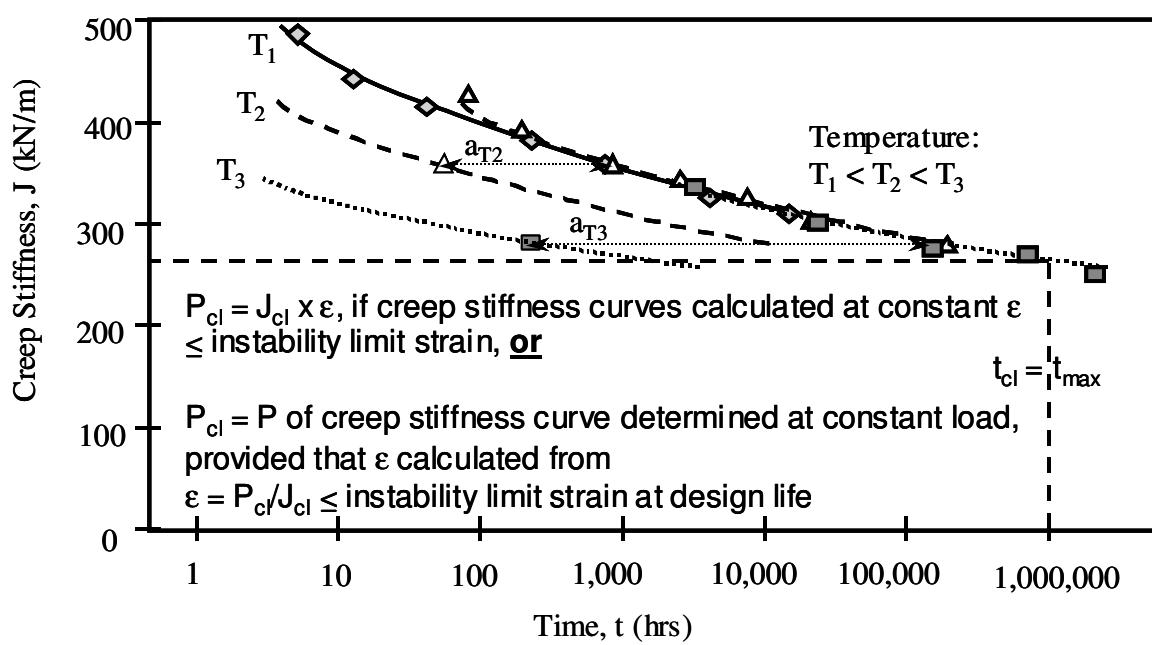
where, J_{cl} is the creep stiffness at the desired design life and temperature, and ε_i is the instability limit strain. If statistical extrapolation beyond the time shifted creep stiffness curves, or beyond the actual data if temperature accelerated creep data is not available, is necessary to reach the specified design life, the calculated creep load T_1 should be reduced by an extrapolation uncertainty factor as follows:

$$T_1 = (J_{cl})(\varepsilon_i)/(1.2)^{x-1} \quad (\text{C.2.1-3})$$

where “x” is the number of log cycles of time the creep stiffness data must be extrapolated. Extrapolations greater than two log cycles of time are not recommended (see Appendix B for a more detailed explanation). The factor $(1.2)^{x-1}$ is the extrapolation uncertainty factor. If extrapolating beyond the actual or time shifted data less than one log cycle, set “x-1” equal to “0”. This extrapolation uncertainty factor only applies to statistical extrapolation beyond the actual or time shifted data using regression analysis and assumes that a shift from ductile to brittle behavior beyond the actual or time shifted data does not occur. This extrapolation uncertainty factor also assumes that the data quality is good, data scatter is reasonable, and that a minimum of 5 load levels for each temperature are tested. The load levels should be well distributed within the load range tested, and at least one to two load levels should be high enough to produce rupture within the test time at each test temperature. If these assumptions are not true for the data in question, this uncertainty factor should be increased. The uncertainty factor may also need to be adjusted if a method other than the one presented in detail herein is used for extrapolation. This will depend on how well that method compares to the method provided in this appendix. This extrapolation uncertainty factor should be increased to as much as $(1.4)^x$ if there is the potential for a shift from ductile to brittle behavior to occur beyond the actual or time shifted data, or if the data quality, scatter, or amount is inadequate (see Appendix B, Notes 5 and 6). Furthermore, if the data quality is inadequate, it may be necessary to begin applying the extrapolation uncertainty factor before the end of the time shifted data.



(a) Creep stiffness curves and determination of shift factors.



(b) Extrapolation of creep stiffness curves and determination of creep limit.

Use of Time-Temperature Superposition to Extrapolate Creep Stiffness Curves.
Figure C.2.1-1

C.2.2 Step-By-Step Procedures for Extrapolating Creep Strain Data – Stepped Isothermal Method (SIM)

See Appendix B for details regarding the description of SIM and issues regarding its use. SIM can be considered for use in generating and extrapolating geosynthetic creep data provided this method is shown to produce results which are consistent with the “conventional” extrapolation techniques recommended in this appendix. To this end, creep testing shall be conducted using conventional tests (ASTM D5262) and SIM tests (ASTM D6992). At least six SIM creep tests and six conventional creep tests shall be conducted on at least one of the products in the product line being evaluated. The load levels selected for the SIM tests and the conventional tests shall be the same. The range of load levels for both types of tests shall be evenly distributed between loads near the creep limit typical for the type of geosynthetic and polymer tested and load levels high enough to result in failure in approximately 100 hours or less (shifted time for SIM, unshifted time for conventional tests). All of the conventional creep tests shall be obtained at the reference temperature (i.e., not temperature shifted). The minimum duration of all of the tests shall be 1,000 hours or more (unshifted for conventional tests and time shifted for SIM).

The comparison between the SIM and conventional creep tests data shall be performed at a specified strain. The specified strain will depend on the strains observed in all of the creep tests (SIM and Conventional). Select a strain that will intercept all of the creep curves as much as possible. Preferably, the strain level should be approximately 5 to 10% or more. Where the selected strain level intersects each creep curve, determine the time required to reach the specified strain. Plot the load level as a function of the logarithm of time to reach the specified strain for each set of data, and perform a regression for each data set. Use the confidence limit test for comparing SIM to conventional data as described in Appendix B, using Equations B.3-1 and B.3-2. The log times to the specified strain level shall be determined at a load level that corresponds to 1,000 hours and 50,000 hours on the conventional creep envelope, for both data sets. The log time to rupture for the SIM regression at this load level shall be within the upper and lower 90% confidence limits of the mean conventional regressed time to the specified strain at the same load level using Student's *t* test (see Appendix B for details regarding how to calculate this).

If this requirement is not met, perform two additional SIM tests at each load level *P* for the specified *t_{reg}* where this comparison was made and develop a new SIM time to the specified creep strain envelope using all of the SIM data. If for the revised SIM regression envelope resulting from these additional tests this criterion is still not met, perform adequate additional conventional creep rupture testing to adequately establish *T_l* for the product in accordance with this appendix.

If the criterion provided above is met, the SIM testing shall be considered to be consistent with the conventional data, and SIM may be used in combination with the conventional data to meet the requirements of this appendix regarding the number and duration of creep tests. In this case, the SIM data can be used to establish an isochronous curve at the specified design life (see Figure C.1-4). Once established, using a strain level equal to the instability strain limit for the product determined in accordance with Figure C.1-3 and

Section C.1, determine the load P_{cl} directly from the isochronous curve and calculate the creep limit load T_1 .

C.3 Determination of RF_{CR}

The creep reduction factor, RF_{CR} , is determined by comparing the long-term creep strength, T_1 , to the ultimate tensile strength (ASTM D4595 or ASTM D6637) of the sample tested for creep. The sample tested for ultimate tensile strength should be taken from the same lot, and preferably the same roll, of material that is used for the creep testing. For ultimate limit state design, the strength reduction factor to prevent long-term creep rupture is determined as follows:

$$RF_{CR} = \frac{T_{lot}}{T_1} \quad (C.3-1)$$

where, T_{lot} is the average lot specific ultimate tensile strength (ASTM D4595 or ASTM D6637) for the lot of material used for the creep testing. Note that this creep reduction factor takes extrapolation uncertainty into account, but does not take into account variability in the strength of the material. Material strength variability is taken into account when RF_{CR} , along with RF_{ID} and RF_D , are applied to T_{lot} to determine the long-term allowable tensile strength, as T_{ult} is a minimum average roll value. The minimum average roll value is essentially the value that is two standard deviations below the average value.

C.4 Estimation of Long-Term Creep Deformation

In-isolation creep strain data can be used to estimate post-construction strains and deformations (see Allen and Bathurst, 2002b). Since load levels in full scale structures as a percent of the ultimate tensile strength are generally quite low, adequate creep data must be obtained at low load levels (typically in the range of 2 to 20% of ultimate). The key to accurate estimation of creep strains in full scale structures is an accurate prediction of the load level.

Step 1: Estimate the load levels in the reinforcement layer(s). Current design specifications (AASHTO 2004, 2002) use the Simplified Method to estimate reinforcement loads in walls, or slope stability analysis techniques (Elias, et al., 2001) to assess reinforcement loads in reinforced slopes. Loads should be estimated for this purpose without any factor of safety or load factor applied. Based on the results obtained by Allen and Bathurst (2002a), the methods provided in current design specifications and guidelines tend to significantly over-predict reinforcement load levels in geosynthetic structures. A new method (the K-Stiffness Method) has been developed by Allen et al. (2003) that appears to predict reinforcement loads in geosynthetic structures much more accurately.

Step 2: From the available creep strain data, create isochronous curves (see Section C.1 and Figure C.1-4).

Step 3: Use the isochronous curves to create a creep strain curve at the desired load level, by selecting the strains at each time at the selected constant load level.

Step 4: Select the portion of the creep strain curve that is applicable to the post-construction strains in the full scale structure, accounting for the time required to build the structure (see Figure C.4-1).

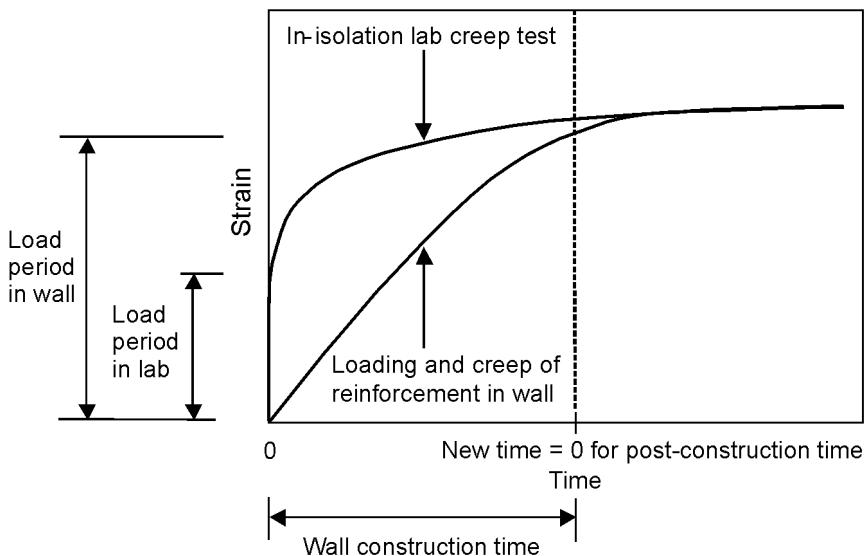


Figure C.4-1. Conceptual illustration showing adjustment of reinforcement creep strains measured in walls to in-isolation laboratory creep data (after Allen and Bathurst, 2002b).

Step 5: The creep strain is calculated as the strain at the desired design life plus the time required for the construction of the geosynthetic structure minus the strain at the end of the geosynthetic structure construction.

C.5 Estimation of Creep Stiffness for Working Stress Design

Strains for working stress design, such as when using the K-Stiffness Method (Allen et al., 2003) are typically small (i.e., approximately 2%). Since reinforcement stiffness is generally a nonlinear function of strain, it is important to obtain the creep stiffness at the appropriate strain level. The primary purpose of this stiffness calculation is to provide input data for working stress methods such as the K-Stiffness method (Allen, et al., 2003), or for more sophisticated analyses such as finite element or finite difference numerical simulations. Typically, the stiffness at the end of structure construction (J_{EOC}) or at the end of the structure design life (J_{DL}) would be required as input for this type of analysis. Either “conventional” creep testing may be used, or SIM may be used if SIM is determined to be consistent with the conventional data as described in Section C.2.2.

The load application rate during creep load ramp up should be consistent with the application rate used in the governing tensile test method (e.g., ASTM D4595 or D6637). If it is not possible to accurately apply the load at a specified rate (e.g., if dead weight is applied through the use of a jack), the actual application rate should be measured and recorded.

If it has been shown that single rib/narrow width specimens can be used in lieu of full width specimens for creep testing at high load levels (see beginning of this appendix), single rib/narrow width specimens may also be used for low strain creep stiffness testing if respective short-term tensile tests also indicate no significant specimen width effects. The maximum difference between the mean values of the load at 2 percent strain in the single rib/narrow width tensile tests and the full width tensile tests must be no greater than what is considered statistically insignificant based on a one sided student-t distribution at a level of

The slack tension, T_o , applied to the specimen based on the governing tensile test (e.g., ASTM D4595 or D6337) will likely be too large for creep stiffness testing due to the very low loads that are likely for this type of testing. A maximum slack tension of approximately 10 percent of the anticipated load at 2 percent strain or 9 N (2 lbf), whichever is less, is recommended for single rib or narrow width specimens. For full width specimens (i.e., per ASTM D5262), a maximum slack tension of approximately 10 percent of the anticipated load at 2 percent strain or 70 N (15 lbf), whichever is less, is recommended. Since these maximum slack tension values differ from what is specified in ASTM D4595 and ASTM D6637, a special set of tensile tests may need to be conducted for use with the low strain creep stiffness testing program. ASTM D4595 and ASTM D6637 allow both the slack tension and the slack displacement, d_o , to be set to zero for calculation purposes. For low strain creep stiffness testing, the slack displacement should be set to zero, but the slack tension should be left at its full value for stiffness calculation purposes.

Step 1: Obtain creep strain data for at least one load level low enough to produce a strain level at the end of structure construction (assume to be 1,000 hrs unless otherwise specified by the approval authority). Per agreement between the approval authority and the reinforcement manufacturer, load levels to produce additional 1,000 hour strain levels may be tested. A minimum of two specimens per product at each load level shall be tested.

To establish the load levels needed to produce the desired 1,000 hour strains for each product, conduct a series of 1,000 second ramp and hold (R+H) tests. An initial estimate of the load levels needed for the R+H tests can be obtained from the tensile tests used to establish T_{lot} for each product tested. Test a load level that is likely to produce a strain of approximately 2 percent at 1,000 hours, and then two other load levels to bracket the 2 percent load level (e.g., at load levels that would yield approximately 1 percent strain and 3 to 4 percent strain at 1,000 hours). Do three replicate R+H tests at each of those load levels, plotting the load level as a function of the estimated strain at 1,000 hours, assuming a log linear extrapolation is valid for the R+H test results. Perform a regression analysis of that data to obtain a more accurate estimation of the load level required to produce a strain of 2 percent at 1,000 hours, and run three replicate R+H tests at that load level. If one of the load levels used for the R + H tests does not produce an estimated strain of 2 percent at 1,000 hours, a fourth set of three replicate R+H tests may be needed, estimating the load level based on a regression of the R+H tests for the first three load levels. Then conduct two full 1,000 hour creep tests at the R+H load level that results in the closest estimate to 2 percent strain at 1,000 hours.

Note 1: It is desirable to conduct the full 1,000 hour creep tests at the R+H load levels tested so that a direct comparison can be made between the 1,000 hour creep tests and the R+H tests. If the creep observed in the 1,000 hour creep tests is in fact log linear, the R+H tests can then be used for quality assurance testing in the future.

Step 2: Use the 1,000 hour creep test results, and any other available creep strain data for the same lot of material, to create isochronous creep curves as shown in Figure C.1-4, if the 1,000 hour creep stiffness tests do not achieve a strain of 2 percent (or other specified strain) at 1,000 hours..

Step 3: Create creep stiffness curves at the desired constant strain level (typically 2%) as shown in Figure C.1.5, and extrapolate to the desired time as necessary using the "conventional" approach illustrated in Figure C.2.1-1 or using SIM, if SIM has been determined to be applicable. In general, extrapolation should not be necessary if the "conventional" approach is used. Be sure to extrapolate the creep stiffness curve to the desired effective design temperature. The "conventional" approach (ASTM D 5262) shall be used unless comparative testing is conducted that demonstrated SIM (ASTM D6992) is providing results that are consistent with the "conventional" approach as defined in T 925.

Step 4: Obtain the creep stiffness, J_{EOC} or J_{DL} , at the desired time from the creep stiffness curve as shown in Figure C.2.1-1.

C.6 Evaluation of Product Lines

Appendix B Section B.5 shall be used as the basis to apply creep strain data to product lines for determination of RF_{CR} . For creep stiffness assessment, a minimum of three products in the product line spanning the range of products in the line shall be tested as described in Section C.5. To interpolate to other products between the products tested, determine T_{lot} for each product tested, plotting the creep stiffness values obtained in Section C.5 as a function of T_{lot} . Creep stiffness values for other products in the product line not tested can be interpolated based on their tensile strength.

References

- Allen, T.M., 1991, "Determination of Long-Term Strength of Geosynthetics: a State-of-the-Art Review", *Proceedings of Geosynthetics '91*, Atlanta, GA, USA, Vol. 1, pp. 351-379.
- Allen, T. M., and Bathurst, R. J., 1996, "Combined Allowable Strength Reduction Factor for Geosynthetic Creep and Installation Damage", *Geosynthetics International*, Vol. 3, No. 3, pp. 407-439.
- Allen, T.M., and Bathurst, R.J., 2002a, "Soil Reinforcement Loads in Geosynthetic Reinforced Walls at Working Stress Conditions", *Geosynthetics International, Geosynthetics International*, Vol. 9, Nos. 5-6, pp. 525-566.
- Allen, T.M., and Bathurst, R.J., 2002b, "Observed Long-Term Performance of Geosynthetic Walls, and Implications for Design", in press with *Geosynthetics International, Geosynthetics International*, Vol. 9, Nos. 5-6, pp. 567-606.
- Allen, T.M., Bathurst, R.J., Lee, W. F., Holtz, R. D., and Walters, D.L., 2003, "A New Working Stress Method for Prediction of Reinforcement Loads in Geosynthetic Walls", *Canadian Geotechnical Journal*, Vol. 40, No. 5, pp. 976-994.
- Andrawes, K. Z., McGown, A., and Murray, R. T., 1986, "The Load-Strain-Time Behavior of Geotextiles and Geogrids," *Proceedings of the Third International Conference on Geotextiles*, Vienna, Austria, pp. 707-712.
- Bush, D.I., 1990, "Variation of Long-Term Design Strength of Geosynthetics in Temperatures up to 40°C", Proceedings of the Fourth International Conference on Geotextiles, Geomembranes, and Related Products, The Hague, Netherlands, pp. 673-676.
- den Hoedt, G., Voskamp, W., van den Heuvel, C. J. M., 1994, "Creep and Time-to-Rupture of Polyester Geogrids at Elevated Temperatures," *Proceedings of the Fifth International Conference on Geotextiles, Geomembranes, and Related Products*, Singapore, pp. 1125-1130.
- Ferry, J. D., 1980, Viscoelastic Properties of Polymers, 3rd Edition, John Wiley and Sons, NY.
- Ingold, T.S., Montanelli, F., and Rimoldi, P., 1994, "Extrapolation Techniques for Long Term Strengths of polymer Geogrids," *Proceedings of the Fifth International Conference on Geotextiles, Geomembranes, and Related Products*, Singapore, pp. 1117-1120.
- Jewell, R.A. and Greenwood, J.H., 1988, "Long-Term Strength and Safety in Steep Soil Slopes Reinforced by Polymer Materials", *Geotextiles and Geomembranes*, Vol. 7, Nos. 1 and 2, pp. 81-118.
- Koerner, R. M., 1990, "Determination of the Long-Term Design Strength of Stiff Geogrids," GRI Standard Practice GG4(a).
- Krumm, G., 1988, *Der einfluss mechanischer schadigung auf das kriechverhalten von technischem filament - garn aus polyethylenterphthalat*, Diplomarbeit TU - Aachen.
- McGown, A., Andrawes, K. Z., Yeo, K. C. and DuBois, D.D., 1984, "The Load-Strain-Time Behavior of Tensar Geogrids", *Proceedings of the Symposium on Polymer Grid Reinforcement in Civil Engineering*, Paper No. 1.2, pp. 1-7.

- McGown, A., Paine, N., and DuBois, D.D., 1984a, "Use of Geogrid Properties in Limit Equilibrium Analysis", *Proceedings of the Symposium on Polymer Grid Reinforcement in Civil Engineering*, Paper No. 1.4, pp. 1-5.
- Popelar, C.H., Kenner, V.H., and Wooster, J.P., 1991, "An Accelerated Method for Establishing the Long Term Performance of Polyethylene Gas Pipe Materials", *Polymer Engineering and Science*, Vol. 31, pp. 1693-1700.
- Takaku, A., 1981, "Effect of Drawing on Creep Fracture of Polypropylene Fibers", *Journal of Applied Polymer Science*, Vol. 26, pp. 3565-3573.
- Thornton, J. S., Allen, S. R., and Thomas, R. W., 1997, "Approaches for the Prediction of Long Term Viscoelastic Properties of Geosynthetics from Short Term Tests," *Geosynthetics '97*, IFAI, Long Beach, CA, Vol. 1, pp. 277-291.
- Thornton, J. S., Allen, S. R., Thomas, R. W., and Sandri, D., 1998, "The Stepped Isothermal Method for Time-Temperature Superposition and Its Application to Creep Data of Polyester Yarns," *Sixth International Conference on Geotextiles, Geomembranes, and Related Products*, Atlanta, GA, pp. 699-706.
- Thornton, J. S., Paulson, J., and Sandri, D., 1998, "Conventional and Stepped Isothermal Methods for Characterizing Long-Term Creep Strength of Polyester Geogrids," *Sixth International Conference on Geotextiles, Geomembranes, and Related Products*, Atlanta, GA, pp. 691-698.

WSDOT Test Method No. 925, Appendix D

Product Specific Testing and Data Interpretation Requirements to Determine RF_D for Geosynthetic Reinforcements

This appendix provides guidance regarding the performance of long-term product specific durability testing that may be conducted for product acceptance in lieu of the durability index testing as described in “Determination of Long-term Geosynthetic Strength for Initial Product Acceptance” as provided in this protocol. The procedures that follow are required if it is desired to use a value of RF_D less than the default minimum of 1.3, or to determine RF_D for environments that are defined as aggressive.

This appendix has been developed to address polypropylene (PP), polyethylene (PE or HDPE), and polyester (PET) geosynthetics. While the chemical and biological durability procedures and criteria provided herein may also be applicable to other polymers (for example, hydrolysis testing as described herein is likely applicable to polyamide and PVA geosynthetics), additional investigation will be required to establish a detailed protocol and acceptance criteria for these other polymers. These other polymers may be considered for evaluation using this protocol once modifications to the chemical/biological durability aspects of this protocol have been developed and are agreed upon by the approval authority.

The product specific durability studies for the determination of RF_D should be conducted in, or if necessary extrapolated to, the chemical/biological environment anticipated in the reinforced backfill. The anticipated temperature of the environment is also a key variable in assessing the durability of a given product, as temperature can have an exponential effect on the rate of product property change. For the purposes of these guidelines, the effective design temperature is defined as the temperature that is halfway between the average yearly air temperature and the normal daily air temperature for the highest month at the wall site. Higher design temperatures may need to be considered for structures with southern exposures. The effective design temperature will be assumed to be 20° C (68° F), if the design temperature is not specifically identified in the contract specifications. Therefore, determine RF_D at a temperature of 20°C (68° F) as a minimum. Determination of RF_D at higher temperatures is optional.

Standards are currently not available for determining the effect of chemical/biological activity on long-term geosynthetic reinforcement strength. However, long-term product specific durability testing can be conducted in a manner that is likely to produce safe results. Geosynthetic durability can be evaluated using either retrieval and testing of geosynthetics in actual installations, or through long-term accelerated laboratory testing. Use of field retrieval data from actual installations requires that the baseline, in terms of tensile strength before and immediately after installation, and possibly other properties, be known with certainty, and that the observation period be of sufficient length to permit extrapolation to the desired design life. The field retrieval approach is in general fraught with practical and technical difficulties (see Allen and Elias, 1996, Elias, 2000, and Elias, 2001). Furthermore, long periods of time may be needed for polyolefins to establish trends that can be extrapolated due to the presence of antioxidants, as no loss in strength will be observed until the antioxidants are used up. Elias (2001) suggests that 30 years of in-service time may be required to obtain adequate observational data for polyolefins, and

even PET products may require 20 years of in-service observations or more to accomplish this. Because of the very long observation periods required, long-term laboratory durability testing is the more practical approach to dealing with the durability issue. An overview of an appropriate laboratory testing approach for each geosynthetic polymer type is provided.

For polyolefin products in which the fibers/ribs do not exhibit micro-cracks or crazes as manufactured, long-term chemical durability testing may consist of elevated temperature oven aging tests to evaluate potential for oxidation effects (FHWA, 1997; Elias, et. al., 1997; Salman, et. al., 1998; Elias, et al., 1999). A magnification of x2,000 to x3,000 may be needed to observe whether or not micro-cracks or crazes are present (Salman, et. al., 1997). If micro-cracks or crazes are present, elevated temperatures may significantly affect the molecular structure of polyolefins in the vicinity of the micro-cracks/crazes, making extrapolation of elevated temperature oxidation behavior to the behavior of the as-manufactured product at ambient temperatures very difficult (Salman, et. al., 1998).

For polyolefins in which the fibers/ribs exhibit micro-cracks or crazes, a means other than elevated temperature may be needed to accelerate oxidation behavior. Salman, et. al. (1998) suggest that elevated oxygen concentration and pressure at ambient temperature may prove to be an effective accelerator in lieu of elevated temperature, especially for geosynthetic products in which the fibers/ribs exhibit micro-cracks or crazes as manufactured. In addition, Schröder et al (2002) have performed extensive testing and development of a protocol utilizing elevated oxygen pressure to address this issue. However, long-term validation of the protocol and final development of the protocol as a test standard are yet to be performed.

If oven aging tests are conducted, a forced air oven is strongly recommended to keep the environment inside the oven as uniform as possible during the entire test duration and to keep oxidation products from building up inside the oven, considering the long durations that are likely to be required. Temperature uniformity inside the oven should be maintained at + 1%. An oven with horizontal air flow is recommended. Specimens should be placed in the oven parallel to the air flow and spaced no closer together than 13 mm (0.5 in.) apart (Allen and Elias, 1996; Elias, et al., 1999). The specimens should not be framed to prevent shrinkage, if shrinkage occurs, as doing this will create load in the specimen, making the resulting data difficult to interpret. Note that oxidation testing using forced air ovens will produce conservative estimates of long-term product strength due to the rapid air circulation and the relatively high oxygen content in the oven relative to the oxygen content in the ground. If the geosynthetic supplier wishes to submit data at a lower oxygen content than that of air (approximately 21% O₂), use of such data for approval of a given product may require that the structure be declared experimental, requiring that instrumentation be placed in the ground to verify the actual oxygen content in the structure backfill.

Alternatively, the geosynthetic supplier could submit data from previously constructed structures with similar backfill in which the actual oxygen content in the structure backfill was measured.

For polyesters, long-term chemical durability testing should consist of elevated temperature immersion tests to evaluate potential for hydrolysis effects. A reactor similar to that illustrated in Elias, et al. (1999) is recommended for incubating the geosynthetic specimens. A description of the test protocol is provided by Elias, et al. (1999). The reactor should be capable of maintaining temperature uniformity (+ 1%) and stability during long-term use. A minimum solid/liquid ratio of 1:40 should be used to size the reactor and to determine the maximum number of specimens that can be placed in the reactor. Measures should be taken to minimize possibilities for oxidation and reaction with carbon dioxide during the long-term incubation (e.g., replace any air inside the reactor with nitrogen, use de-aired water, keep system well sealed, etc.). 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., Teflon, stainless steel, etc.). The specimens should not be framed to prevent shrinkage, if shrinkage occurs so that an unknown amount of tension is not placed on the specimens. Specimens should each be separated by a distance of at least 13 mm (0.5 in.). The solution should be intensively stirred to ensure solution uniformity. For coated polyester products, the immersion tests should be conducted without the coating or the coated specimen ends should not be recoated (i.e., the ends of the core polymer should be left exposed to the immersion liquid). Elevated temperatures should be used to accelerate the degradation process, which allows the data to be extrapolated to the desired design life. Hydrolysis data should be submitted for the product at a pH of approximately 7 (i.e., neutral conditions - distilled water), at a pH of 9 or more, and at a pH of 4 or less to facilitate the determination of RF_D . RF_D should be determined at a pH of 7 and at an alkaline pH (i.e., a pH of 9) as a minimum. If very acidic soils are anticipated (i.e., a pH near the bottom limit of pH = 4 for conditions defined as nonaggressive), RF_D should be determined at a pH of 4 as well.

Note that EPA 9090 testing, or the ASTM equivalent (ASTM D5322), is not considered adequate for a laboratory testing program to provide an estimate of RF_D . However, EPA 9090 or ASTM D5322 testing can be used as a first cut screening tool. That is, if any significant degradation of the strength of the product in question is observed for the chemical environment tested, the product would be disqualified for use in that chemical environment unless longer term testing conducted in accordance with this appendix is performed. EPA 9090 testing (or ASTM D5322) could also be used verify the effects of certain environmental variables which are known, based on the literature, to not significantly affect the given material. For example, low or high pH is known, based on the literature, to have little effect on polyolefins. This type of testing could be used to verify that the low or high pH does not affect the tensile strength of a polyolefin product, to allow that product to be used in environments that have a pH outside the range defined as a nonaggressive environment.

The long-term chemical durability testing program should be conducted and interpreted using the following guidelines:

- Incubation temperatures for the testing should be high enough to adequately accelerate the degradation process but below any major transitions in polymer behavior (e.g., glass transition, melting). Maximum recommended test temperatures to avoid major transitions are on the order of 70 to 75° C for polypropylene, high density polyethylene, and polyester, except as discussed above for polyolefin products which have micro-cracks or crazes as manufactured. However, exposure to temperatures near the upper end of these ranges could affect the stress-strain behavior of the material due to loss of molecular orientation, or possibly other effects that are not the result of chemical degradation. Therefore, care needs to be exercised when interpreting results from strength testing after exposure to temperatures near the maximum test temperatures indicated above. In general, if the stiffness of the material after exposure to the environment is significantly different from that of the virgin material, the stress-strain properties, and possibly the strength, of the material may have been affected by the exposure temperature in addition to the chemical environment. If the stiffness has been affected, the cause of the stiffness change should be thoroughly investigated to determine whether or not the change in stiffness is partially or fully due to the effect of temperature, or alternatively not use the data obtained at and above the temperature where the stiffness was affected. It is additionally recommended that the Arrhenius plot of the data be checked for linearity (see the discussion of Arrhenius modeling which follows). As a minimum, two to three data points above and below the suspected transition should be obtained and the plot checked for linearity through the entire range of temperatures, if it is desired to validate the use of data above the suspected transition for Arrhenius modeling and extrapolation purposes.
- A minimum of three to four test temperatures are recommended, typically spaced monotonically at 10° C increments (e.g., see ASTM D3045), except as discussed above for some polyolefin products.
- At the lowest test temperature (e.g., 30 to 50° C), incubation times of 2 to 4 years should be anticipated to get data adequate for long-term extrapolation.
- Enough retrievals (e.g., a minimum of three to four retrievals) should be made at a given test condition to adequately define the property loss as a function of incubation time.
- As a minimum, degradation should be tracked using the tensile strength of the specimens retrieved from the incubation chambers. Full wide width (ASTM D4595 or ASTM D6637) specimens are preferred; however, single rib or yarn specimens can be used.
- It is also recommended that degradation be tracked by chemical means, if possible, as well as through the use of scanning electron microscope (SEM) micrographs to verify the significance of the mechanical property degradation observed.

- The statistical variation of the measured properties after degradation are likely to be greater than what would be observed for the virgin material. This may require that the number of specimens per retrieval be greater than what the property variation for the virgin material would indicate.
- Extrapolation of chemical durability data for polymers typically utilizes an Arrhenius approach, though there is evidence which suggests that the Arrhenius model does not always work well for geosynthetics. Assuming Arrhenius modeling is appropriate, the slope of the strength degradation versus time plots (transformed mathematically to be linear through zero, first, or second order Arrhenius equations) can be used to characterize the degradation behavior as a function of temperature, allowing the slope at the desired design temperature to be estimated through the Arrhenius extrapolation. The equation order which best fits the data should be used (see Salman, et. al., 1998, for details). The strength retained at a given time at the design temperature can be calculated directly from the linear equation with the extrapolated slope. Note that Arrhenius modeling could also be conducted as a function of reactant (oxygen) concentration and pressure instead of temperature (Shelton and Bright, 1993; Salman, et. al., 1998). The extrapolation concept would be similar to that used for temperature. See Shelton and Bright (1993), Salman, et. al. (1997), and Salman, et. al. (1998), Elias, et al. (1999), Elias (2000) for guidance on Arrhenius modeling techniques as applied to geosynthetics. Also note that since the extrapolation is being conducted over several log cycles of time, uncertainty in the data should be considered when determining the retained strength at the design life and design environment.
- For polyolefin oxidation, Arrhenius modeling will likely need to be conducted in two steps, as there are two main phases in the oxidation process for polyolefins: 1) the induction phase, where antioxidant consumption is the primary activity and little, if any, product strength loss occurs, and 2) the main polymer oxidation phase, where oxidative degradation of the polyolefin occurs, resulting in strength loss, and can generally be described by the kinetics of a Basic Auto-oxidation Scheme (Salman, et. al., 1997; Elias, et al., 1999). An Arrhenius model for the first phase should be developed so that the induction period t^{ind} at the design temperature or reactant (i.e., oxygen) concentration can be estimated. A second Arrhenius model should then be developed using only the data after the induction period, and time in this case would begin at the end of the induction period at each temperature or reactant concentration tested. This second Arrhenius model is then extrapolated to the design temperature or reactant concentration to estimate the strength loss anticipated at the desired design life minus the induction period. Analysis of the remaining antioxidant content provides an additional method of measuring the duration of Step 1, particularly at lower temperatures and long durations, since changes in the antioxidant content take place ahead of the reduction in strength. Note that if the estimated induction period at the design environment is greater than the desired design life, this second phase Arrhenius modeling is unnecessary.

- Once the tensile strength at a given design life and design temperature has been estimated from the test data, determine RF_D as follows:

$$RF_D = \frac{T_{lot}}{T_D} \quad (D-1)$$

where, T_{lot} is the average lot specific ultimate tensile strength for the lot of material used for the durability testing, and T_D is the extrapolated (i.e., to the required design life) lot specific tensile strength after degradation based on the laboratory aging tests. In no case should RF_D be less than 1.1.

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 of burrowing animals such as rabbits. For this reason it is not in general necessary to apply consider biological degradation in defining RF^D . However, the possibility of biological degradation should be reviewed if new polymers other than those described are used. Biological durability, if specifically requested by the approval authority, should be evaluated based on ASTM D3083-89, except the test should be modified to use ASTM D4595 or ASTM D6637 as the tensile test method. If any significant tensile strength loss is observed, as determined using ASTM D4595 or ASTM D6637, additional longer term testing should be performed before the product is further considered for use in reinforcement applications (see Bright, 1993).

If, as an alternative to long-term laboratory testing, the geosynthetic manufacturer prefers to submit data from long-term field retrievals, the following requirements must be met:

- A minimum of three retrievals must be obtained over a minimum time period adequate to permit extrapolation to the required design life (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 minimum study period).
- The retrieved samples shall be evaluated both physically and chemically to determine changes in strength, fiber/yarn/rib appearance, and polymer chemistry. Lot specific baseline data for the exhumed geosynthetic regarding strength and polymer properties must be available for comparison. The soil environment in which the geosynthetic was placed must also be well defined in terms chemistry, moisture, temperature, gradation, and approximate geosynthetic stress level. Enough specimens for each retrieval must be taken to account for statistical variance in the properties measured. See Elias (2000, 2001) for a more detailed description of the procedures required to obtain the needed information to determine RF_D using this approach.
- The polymer and physical characteristics of the exhumed material must meet the requirements for use in determining RF_D for “similar” products as described later in this appendix.

Note 1: *Chemical degradation of geosynthetics is a result of both environmental factors and polymer compositional factors. For a given polymer type, one can expect the greatest amount of chemical degradation to occur, in general, with polymers which have low molecular weights, low percent crystallinity, low density, and low draw ratios (Elias, 1990). Polymer additives also influence the degradation rate. Regarding environmental factors, one can expect the greatest amount of degradation to occur, in general, at relatively high temperatures, in moderate to high moisture conditions, in soils which are active chemically (especially in terms of pH and certain types of ions present), and with the geosynthetic under stress (Elias, 1990). Thickness of the polymer fibers may also have a strong influence on the degradation rate, as degradation mechanisms are dependent on diffusion processes or exposure and removal of surface material (Wrigley, 1987). Key chemical degradation mechanisms in typical soil environments include oxidation, hydrolysis, and environmental stress cracking (ESC).*

The oxidation reaction can either be initiated by ultraviolet (UV) radiation or thermal energy. The rate of oxidation will be governed by chemical rate kinetics and by the rate of diffusion of the oxygen, the antioxidants and the degradation products. Diffusion (or migration) is frequently the controlling factor. Where the geosynthetic is buried, thermally activated oxidation is of most interest. UV activated oxidation is of importance only where the geosynthetic is exposed to light, such as at the wall face. In general, the wall face is covered from light with a permanent facing. Of the polymers used in geosynthetics, relatively speaking, polypropylene (PP) is potentially the most susceptible to oxidation, followed by high density polyethylene (HDPE) and polyester (PET) which have a relatively low susceptibility. Though in actuality a rather complex reaction, conceptually, polyolefin (i.e., PP and HDPE) oxidation is the reaction of free radicals within the polymer with oxygen, resulting in breakdown and/or crosslinking of the molecular chains and embrittlement of the polymer.

Antioxidants are typically added to the polymer (sometimes multiple types are added to increase effectiveness) to prevent oxidation during processing and use. Broad classes of antioxidants often used in geosynthetics include phenolic stabilizers and hindered amine light stabilizers (HALS). As the antioxidants are used up, resistance of the polymer to oxidation will decrease. The rate of polymer oxidation is dependent on how much and what type of antioxidant is present initially, at what rate it is used up, and how well it is distributed within the polymer (Van Zanten, 1986). Environmental factors which affect the rate of oxidation include temperature, oxygen concentration which in soil can vary from 21% in gravels at shallow depth to on the order of 1% in fine-grained soils at deeper depths (Yanful, 1993; Yanful, et. al., 1993), and the presence of transition metal ions such as iron (most common) or copper which act as a catalyst and accelerate the oxidation reaction. Thermal oxidation at typical in-soil temperatures appears to be quite slow.

Of the polymers mentioned above, only PET is potentially susceptible to hydrolysis. Hydrolysis occurs when water molecules react with the polymer molecules, resulting in chain scission, reduced molecular weight, and strength loss. Hydrolysis is simply the very slow inverse reaction of the synthesis of PET when water is present. The specifics of the reaction vary depending on the pH of the liquid. This results in high pH (alkaline) hydrolysis being relatively rapid, whereas neutral or low pH conditions can result in a slow hydrolysis rate. The rate of hydrolysis is also highly temperature dependent and

can become relatively rapid at high temperatures in the vicinity of the glass transition temperature or above for the polymer, which is on the order of 70° C to 80° C (160° F to 180° F). The polymer does not need to be submerged for hydrolysis to occur, as hydrolysis can occur in moderate to high humidity conditions, though the reaction rate becomes slower as the humidity decreases (McMahon, et. al., 1959).

Hydrolysis appears to be the result of both a surface erosional phenomenon as well as a diffusional process of water to the polymer fiber core. These two phenomena have given rise to the terms "outer" and "inner" hydrolysis. Outer, or surficial, hydrolysis is dominant in high pH conditions and is characterized by loss in fiber cross-sectional area with minimal reduction in the molecular weight of the polymer that remains (Anderson, et. al., 1992; Jailloux, et. al., 1992). Inner, or diffusional controlled hydrolysis is dominant in neutral and acidic conditions and is characterized by significant losses in molecular weight of the polymer with minimal surficial erosion or damage (Anderson, et. al., 1992; Jailloux, et. al., 1992).

Rupture of a polymer when under stress is either ductile or brittle in nature. The ductile failure mode occurs when stresses are high enough to cause tie molecules to stretch out, lamellae to separate and start unfolding, resulting in fracture of the spherulites and plastic flow of the molecular structure (Lustiger, 1983). When failure occurs in a brittle manner, stress levels are usually lower, allowing sufficient time for tie molecules to slowly disentangle themselves from adjacent spherulites, initiating crack formation followed by slow crack growth (Bright, 1993).

ESC is the result of an accelerated crack initiation and growth process occurring when a polymer is subjected concurrently to a particular chemical environment and long-term stress. This accelerated crack initiation and growth process can result in premature brittle failure. ESC results in molecular chain disentanglement rather than chain breakage or chemical change.

Evaluation of ESC has been focused on polyethylene due to its use in various critical applications (e.g., telephone transmission cables, natural gas pipe) and the potential sensitivity of some polyethylenes to this phenomenon. The literature indicates that other polymers used for geosynthetics may also experience some sensitivity to this phenomenon (Bright, 1993).

The results of previous studies show that polyethylene resistance to ESC can be improved by increasing its average molecular weight, decreasing its molecular weight distribution, increasing its crystalline content, reducing the crystallite and/or spherulite size, increasing the degree of orientation, and using copolymerization (Wrigley, 1987). Therefore, the potential for ESC in a given polymer can be controlled.

ESC is closely related to the more general phenomenon of stress cracking. The difference between the two is that the chemical present for ESC accelerates the chain disentanglement process, whereas in stress cracking no accelerating chemical is present. Chemicals identified in the literature that can accelerate the stress cracking process include water, weak acids and bases, alcohols, metallic soaps, and solvents (Wrigley, 1987). Water, and to some extent weak acids and bases, are "chemicals" which need to be considered for ESC in typical in-soil environments.

An extensive long-term laboratory study of oxidation and hydrolysis as applied to geosynthetic reinforcement has been carried out (Elias, et al., 1999). Field studies have been carried out to evaluate many of the longer-term installations in which some baseline data was available (Elias, 2001). In most cases, degradation has been minimal, if it is even significant enough to be measurable. These laboratory studies appear to corroborate the lack of degradation that has been observed in the field (Elias, 2001). The protocols for oxidation and hydrolysis evaluation provided in this appendix, as well as the durability evaluation criteria provided elsewhere in Standard Practice T925, have been developed based on results from the laboratory and field studies conducted by Elias, et al. (1999) and Elias (2001).

Use of Durability Data from “Similar” Products

Long-term chemical/biological durability 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 or both of the following conditions are met:

- The chemical and physical characteristics of tested products and proposed products are shown to be similar. Research data, though not necessarily developed by the product manufacturer, should be provided which shows that the minor differences between the tested and the untested products will result in equal or greater chemical/biological degradation resistance for the untested products.
- A limited testing program is conducted on the new or similar product in question and compared with the results of the previously conducted full testing program.

For polyolefins, similarity could be judged based on molecular weight and structure of the main polymer (i.e., is the polymer branched or crosslinked, is it a homopolymer or a blend, percent crystallinity, etc.), percentage of material reprocessed, tenacity of the fibers and processing history, and polymer additives used (i.e., type and quantity of antioxidants or other additives used). For polyesters and polyamides, similarity could be judged based on molecular weight or intrinsic viscosity of the main polymer, carboxyl end group content, percent crystallinity, or other molecular structure variables, tenacity of the fibers and processing history, percentage of material reprocessed or recycled, and polymer additives used (e.g., pigments, etc.). The untested products should also have a similar macrostructure (i.e., woven, nonwoven, extruded grid, needlepunched, yarn structure, etc.) and fiber dimensions (e.g., thickness) relative to the tested products. It should be noted that percent crystallinity is not a controlled property and there is presently no indication of what an acceptable value for percent crystallinity should be.

For chemical durability evaluation, the limited testing program could consist of laboratory aging tests with a 1,000 to 2,000 hour incubation period in the same environment used for the full testing program conducted previously, conducted at a temperature near but slightly below any major property transitions. These limited durability test results must show that the durability 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 program on the older or similar product could be used for the new/similar product. If not, then a full testing and evaluation program for the new product should be conducted.

References

- AASHTO, 2002, *Standard Specifications for Highway Bridges*, American Association of State Highway and Transportation Officials, Seventeenth Edition, Washington, D.C., USA, 686 p.
- Allen, T. M., and Elias, V., 1996, *Durability of Geosynthetics for Highway Applications - Interim Report*, FHWA-RD-95-016, Washington, D.C.
- Anderson, P. L., Jailloux, J.-M., and White, D. F., 1992, "Testing Durability of Polyester to Be Used in Earth-Reinforced Structures," *Earth Reinforcement Practice*, Balkema, Rotterdam, pp. 9-12.
- American Society for Testing and Materials (ASTM), 1994, *Annual Book of Standards*, Vol. 8.04, Elastic Pipe and Building Materials, ASTM, Philadelphia, PA, USA.
- American Society for Testing and Materials (ASTM), 1994, *Annual Book of Standards*, Vol. 4.08 and 4.09, Soil and Rock, ASTM, Philadelphia, PA, USA.
- Bright, D. G., 1993, "The Environmental Stress Cracking of Polymers Used in Geosynthetic Products," *Geosynthetics '93 Conference*, Vancouver, B.C., pp. 925-934.
- Elias, V., 1990, Durability/Corrosion of Soil Reinforced Structures, FHWA/RD-89/186, Federal Highway Administration, Washington, D.C.
- Elias, V., 2000, *Corrosion/Degradation of Soil Reinforcements for Mechanically Stabilized Earth Walls and Reinforced Soil Slopes*, FHWA-NHI-00-044, Federal Highway Administration, Washington, D.C.
- Elias, V., 2001, *Long-Term Durability of Geosynthetics Based on Exhumed Samples from Construction Projects*, FHWA Report FHWA RD-00-157, 53 pp.
- Elias, V., Salman, A., Juran, I., Pearce, E., and Lu, S. 1999, *Testing Protocols for Oxidation and Hydrolysis of Geosynthetics*, FHWA Report FHWA RD-97-144, 200 pp.
- Elias, V., DiMaggio, J., and DiMillio, A., 1997, "FHWA Technical Note on the Degradation-Reduction Factors for Geosynthetics," *Geotechnical Fabrics Report*, Vol. 15, No. 6, pp. 24-26.
- Federal Highway Administration (FHWA), 1997, "Degradation Reduction Factors for Geosynthetics," *Federal Highway Administration Geotechnology Technical Note*.
- Jailloux, J.-M., Anderson, P. L., and Thomas, R., 1992, "Chemical Compatibility Studies of Polyester Fibers and Yarns to Be Used in Geocomposites," *Geotextiles and Geomembranes*, Vol. 11, No. 3, pp. 277-290.
- Jewell, R.A. and Greenwood, J.H., 1988, "Long-Term Strength and Safety in Steep Soil Slopes Reinforced by Polymer Materials", *Geotextiles and Geomembranes*, Vol. 7, Nos. 1 and 2, pp. 81-118.
- Lustiger, A., 1983, "The Molecular Mechanism of Slow Crack Growth in Polyethylene," Proceedings, Eighth Plastic Fuel Gas Pipe Symposium, American Gas Association: Arlington, Virginia, pp. 54-56.

- McMahon, W., Birdsall, H. A., Johnson, G. R., and Camilli, C. T., 1959, "Degradation Studies of Polyethylene Terephthalate," *Journal Chemical Engineering Data*, Vol. 4, No. 1, pp. 57-79.
- Murray, R. T. and Farrar, D. M., 1988, "Temperature Distributions in Reinforced Soil Retaining Walls," *Geotextiles and Geomembranes*, No. 7, pp. 33-50.
- Salman, A., Elias, V., Juran, I., Lu, S., and Pearce, E., 1997, "Durability of Geosynthetics Based on Accelerated Laboratory Testing," *Geosynthetics '97*, IFAI, San Diego, CA, pp. 217-234.
- Salman, A., Elias, V., and DiMillio, A., 1998, "The Effect of Oxygen Pressure, Temperature, and manufacturing Processes on Laboratory Degradation of Polyolefin Based Geosynthetics," *Sixth International Conference on Geotextiles, Geomembranes, and Related Products*, Atlanta, GA (in press).
- Schröder H. F., Bahr H., Lorenz E., Kneip E., Schmücking I., Zeylanov E. B., "Resistance of polyolefin geosynthetics to oxidation – a new accelerated test working at elevated oxygen pressure. Geosynthetics – State of the art – Recent developments," eds Delmas P., and Gourc J P., *Proceedings of the Seventh International Conference on Geosynthetics*, Nice, France. Balkema, Lisse, Netherlands, 2002, pp 1455-1458.
- Shelton, W. S., and Bright, D. G., 1993, "Using the Arrhenius Equation and Rate Expressions, to Predict the Long-Term Behavior of Geosynthetic Polymers," *Geosynthetics '93 Conference*, Vol. 2, Vancouver, B.C., pp. 789-802.
- Van Zanten, V., ed., 1986, *Geotextiles and Geomembranes in Civil Engineering*, Wiley-Halsted.
- Wisse, J.D.M., Broos, C.J.M., and Boels, W.H., 1990, "Evaluation of the Life Expectancy of Polypropylene Geotextiles Used in Bottom Protection Structures Around the Ooster Schelde Storm Surge Barrier - A Case Study", *Proceedings of the Fourth International Conference on Geotextiles, Geomembranes, and Related Products*, The Hague, Netherlands, pp. 679-702.
- Wrigley, N. E., 1987, "Durability and Long-Term Performance of Tensar Polymer Grids for Soil Reinforcement," *Materials Science and Technology*, Vol. 3, pp. 161-170.
- Yanful, E. K., 1993, Oxygen Diffusion Through Soil Covers on Sulphidic Mine Tailings," *ASCE Journal of Geotechnical Engineering*, Vol. 119, No. 8, pp. 1207-1228.
- Yanful, E. K., Riley, M. D., Woyshner, M. R., and Duncan, J., 1993, "Construction and Monitoring of a Composite Soil Cover on an Experimental Waste-Rock Pile near Newcastle, New Brunswick, Canada," *Canadian Geotechnical Journal*, No. 30, pp. 588-599.

