Overview of Geosynthetic Reinforcement Design

The primary use of the test results obtained from the NTPEP geosynthetic reinforcement testing program is to determine the available long-term (i.e., end of design life, typically 75 years) strength, \( T_{al} \), of the reinforcement. The long-term reinforcement strength needed for design is determined from the following equation:

\[
T_{max} < \frac{T_{ult}}{RF_{ID} \times RF_{CR} \times RF_{D} \times FS}
\]

The available long-term strength, \( T_{al} \), is calculated as follows:

\[
T_{al} = \frac{T_{ult}}{RF_{ID} \times RF_{CR} \times RF_{D}}
\]

Where, \( T_{al} \) is the long-term strength of the geosynthetic. This long-term geosynthetic reinforcement strength concept is illustrated in Figure 1. As shown in the figure, some strength losses occur immediately upon installation, and others occur throughout the design life of the
reinforcement. Much of the long-term strength loss does not begin to occur until near the end of the reinforcement design life.

Figure 1. Long-term geosynthetic reinforcement strength concepts.

The value selected for \( T_{ult} \), for design purposes, is the minimum average roll value (MARV) for the product. This minimum average roll value, denoted as \( T_{MARV} \), accounts for statistical variance in the material strength (see more detailed explanation provided later in this document). Other sources of uncertainty and variability in the long-term strength result from installation damage, creep extrapolation, and the chemical degradation process. 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. Therefore, the MARV of \( T_{ult} \) adequately takes into account variability in the creep strength. Note that the MARV of \( T_{ult} \) is the minimum certifiable tensile strength provided by the product manufacturer.

\( T_{max} \), the tensile load in the reinforcement, is generally determined through geotechnical design of the reinforced soil structure as described in national design specifications (e.g., AASHTO, 2007) and FHWA manuals (e.g., Holtz, et al., 1995; Elias, et al., 2001).

Geosynthetic reinforcement applications where the long-term geosynthetic strength and related design parameters that can be determined from the NTPEP test results are illustrated in Figure 2. Note that pavement base course and subgrade reinforcement with geosynthetics is not included at this time, as there is currently not national agreement on what geosynthetic reinforcement design parameters are important for that application, nor is there agreement on how to mechanistically design a geosynthetic reinforced pavement system. However, it is possible that the data generated through the NTPEP program could eventually be used for that application, once agreement is obtained.
The goal of the geosynthetic reinforcement design is to make sure that the available long-term strength of the reinforcement, $T_{al}$, is greater than the applied tensile load, $T_{max}$, by a minimum desired level of safety (i.e., either the FS, or the combination of load and resistance factors). Therefore, once the geosynthetic reinforced structure design is completed and $T_{max}$ is known, the NTPEP test results, in particular $T_{al}$ as determined from the NTPEP test results, can be used to select products that will meet the $T_{max}$ design requirement.

Focus and Typical Organization of NTPEP Geosynthetic Reinforcement Test Reports

In accordance with WSDOT Standard Practice T925, the test program results provided in NTPEP geosynthetic reinforcement test reports are focused on characterization of the product line, specifically testing representative products within the product line to accomplish that characterization. A product line is defined as a series of products manufactured using the same base polymer/fiber in which the base polymer/fiber 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. Provided this definition is met, it should be feasible to interpolate between the products actually tested to the products not specifically tested for a given test property. The guidelines provided in this document explain how to use the test data to characterize the entire product line with regard to long-term strength, stiffness, and durability properties.

The NTPEP test report for geosynthetic reinforcement provides both index test and performance test results. In general, the NTPEP test report provides a summary of the test results which can be used by state and local agencies to determine the long-term strength parameters (i.e., RF_{ID}, RF_{CR}, and RF_{D}) as well as the secant stiffness at low strain. The detailed test results are provided in appendices attached to the main test report. Specific guidelines for the application of the NTPEP test report data are provided in the sections that follow.
**Determination of \( R_{F_{ID}} \)**

The determination of the magnitude of \( R_{F_{ID}} \) can either be targeted to a maximum characteristic backfill particle size that is consistent with the agency’s standard reinforced soil backfill materials, or \( R_{F_{ID}} \) can be targeted to the characteristic reinforced backfill particle size for a project specific backfill. The NTPEP installation damage test results can be used for either approach.

The effect of installation damage on the tensile strength of a geosynthetic reinforcement product is assessed by comparing the damaged strength of the product (i.e., the strength of the product after exhuming it from the soil after it has been installed) to the lot or roll specific tensile virgin (i.e., undamaged) strength of the product sample used for this installation damage evaluation. This undamaged tensile strength obtained prior to installation is termed \( T_{\text{lot}} \) in T925, and is considered the baseline tensile strength for the product sample used for this evaluation in the NTPEP test program. Hence, we have used the term “\( T_{\text{baseline}} \)” in this document. The NTPEP test report will also use the word “baseline” to describe this tensile strength for the sample.

The degree of installation damage is quantified using the following equation:

\[
P = \frac{T_{\text{dam}}}{T_{\text{baseline}}} \tag{3}
\]

where,

\( P \) is the percentage of strength retained after exposure to installation (i.e., installation damage),

\( T_{\text{dam}} \) is the tensile strength of the material after exposure to installation (i.e., in a damaged condition), and

\( T_{\text{baseline}} \) is the roll specific tensile strength of the material used in the installation damage tests. This “baseline” strength is the strength prior to exposing the material to installation.

All three values for each product and condition tested, and associated statistics, are provided in the NTPEP test report. Example installation damage test results are provided in Figures 3 and 4. Similar plots of the installation damage data, but without the interpretive information, are provided in the NTPEP test reports.
Figure 3. Example of installation damage data for several products that represent a product line, from NTPEP testing, when a strong relationship between a product index property and strength retained is observed.

Figure 4. Example of installation damage data presentation that can be used to interpolate values of strength retained for products not installation damage tested, when a strong relationship between a product index property and strength retained is observed.

Note that many products, especially coated polyester geogrids, will not have the strong relationship between the weight or strength of the product and the degree of installation damage that is illustrated in Figures 3 and 4. For example, for coated polyester grids, the robustness of the coating may control the degree of damage observed. Figures 5 and 6 provide an example of
this. Trend lines for the mean, upper bound, and lower bound for the combination of all the products in the product line tested are shown in Figure 5 to illustrate the general trend in the data. From these trend lines, a mean or minimum value at the desired “d50” can be determined as illustrated in Figures 5 and 6. The installation reduction factor can then be determined as the reciprocal of “P_dmean” or “P_dmin”, or possibly something in between, for example.

![Diagram](attachment:diagram.png)

**Figure 5.** Example of installation damage data for several products that represent a product line, from NTPEP testing, when a weak relationship between a product index property and strength retained is observed.

![Diagram](attachment:diagram2.png)

**Figure 6.** Example of installation damage data presentation that can be used to interpolate values of strength retained for products not installation damage tested, when a weak relationship (or no relationship) between a product index property and strength retained is observed.
Typically, the $d_{50}$ size for the backfill soil is used to relate the degree of installation damage to the backfill soil characteristics. However, other backfill gradation parameters and characteristics could be used instead. The full gradation curves for the soils used in the installation damage testing, aggregate durability test results, and photographs and a description of the aggregate angularity, are provided in the NTPEP test reports.

If it is desired to use one value of strength retained for a given product and standard or otherwise specified backfill, a value of $d_{50}$ or other backfill characteristic at the coarsest end of the gradation specification allowable limits should be used.

Once the strength retained has been determined for the product and specified backfill characteristics, the reduction factor for installation damage, $RF_{ID}$, is determined simply as the inverse of the strength retained (i.e., $1/P$).

[Note: The AASHTO LRFD Bridge Design Specifications and WSDOT Standard Practice T925 recommend that $RF_{ID}$ be no less than 1.1.]

In addition to the full scale field installation damage test results, if requested by the manufacturer, laboratory (bench) scale installation damage test results (i.e., ISO/EN 10319) may also be included in the NTPEP test report. These bench scale installation damage test results should not be used directly to determine $RF_{ID}$, but are intended to be used for quality assurance testing purposes in lieu of full scale field installation damage testing. Provided that baseline bench scale installation damage testing is conducted during NTPEP product qualification testing, bench scale installation damage tests can be conducted for quality assurance testing purposes, in which case the NTPEP test report will provide the results of the statistical comparison required in T925 to verify that the product has not significantly changed since the NTPEP product qualification testing.

**Determination of $RF_{CR}$**

The creep reduction factor, $RF_{CR}$, is generally only a function of time for a given product and the amount of time extrapolation required to reach the desired design life, provided that product processing changes or polymer source changes have not occurred. This makes selection of the creep reduction factor fairly straight-forward. The NTPEP test report will provide a complete composite creep rupture envelope for the product line, examples of which are shown in Figures 6 and 7. In Figure 6, the full creep rupture envelope was developed using block shifting of rupture envelopes obtained at three temperatures. In Figure 7, the creep rupture envelope using a combination of conventional creep rupture tests at room temperature, plus temperature accelerated creep rupture tests using SIM (Stepped Isothermal Method) is presented. Either approach will result in a similar composite creep rupture envelope. To create a composite creep rupture envelope for a product line, the applied load for each creep rupture point is usually normalized by the roll specific ultimate strength of the geosynthetic sample used for the creep testing. The normalization can be done using Equation 4.
\[ P = \frac{T_c}{T_{\text{baseline}}} \]  

where,

P is the normalized load level in %,

T_c is the constant load applied to the creep test specimen, and

T_{\text{baseline}} is the roll specific ultimate tensile strength for the creep tested sample.

While the creep rupture load can be normalized using other parameters (see T925), ultimate strength is the most common way to normalize the creep data to create the composite envelope.

**Figure 6. Creep rupture envelope created by block shifting of constant load, constant temperature data.**
The NTPEP test report will provide these summary creep rupture plots as well as the detailed test results used to produce these summary plots. In addition, analyses and plots are provided in the test report to address the following issues:

- Whether or not the products claimed by the manufacturer to be within a single product line do in fact meet the statistical requirements in T925 to be defined as such;
- Whether or not SIM is statistically consistent with “conventional” creep tests conducted at the reference temperature in accordance with T925, if SIM tests are conducted; and
- If quality assurance tests are conducted to verify consistency with the previous product qualification test results, whether or not the T925 statistical requirements for that comparison are met.

In general, if the statistical creep data comparisons do not meet T925, additional creep testing is conducted and reported in the NTPEP test report, and the creep rupture composite plots are modified accordingly. Therefore, the composite creep rupture plots provided in the test report can be relied upon to determine $R_{FCR}$.

Using the composite creep rupture plots provided in the NTPEP test report, determine $P_{cl}$ at the desired design life ($t_d$ in Figures 6 and 7). In US design practice, design life is typically 50 to 75 years, though other design lives can be selected depending on the nature of the project. The
variable $t_{\text{max}}$ is the time corresponding to the rupture point at the longest time on the plot. If $t_d$ is more than one log cycle of time beyond $t_{\text{max}}$ in Figure 6 or 7, to determine $RF_{CR}$, extrapolation uncertainty will need to be taken into account using the following equation:

$$RF_{CR} = \frac{T_{\text{baseline}}}{T_d} = \frac{T_{\text{baseline}}}{\left(\frac{P_{cl}}{1.2(10^{-x})}\right)}$$  \hspace{1cm} (5)

Where,

- $T_d =$ factored creep limited tensile strength at design life
- $P_{cl} =$ creep limited strength measured directly from extrapolated creep data at the desired design life (see Fig. 6 or 7)
- $x =$ number of log cycles of time of extrapolation beyond time shifted data
  $\quad = \log t_d - \log t_{\text{max}}$ (see Fig. 6 or 7)

If $t_d$ is less than or equal to one log cycle of time beyond $t_{\text{max}}$ in Figure 6 or 7 simply set $P_{cl}$ equal to $T_d$ to determine $RF_{CR}$ (see Equation 6).

$$RF_{CR} = \frac{1}{P_{cl}}$$  \hspace{1cm} (6)

**Determination of $RF_D$**

The reduction factor for long-term durability, $RF_D$, is not determined directly from the NTPEP test results, but is correlated to index test results that have been correlated to long-term geosynthetic degradation performance based on long-term research. A geosynthetic product or product line is considered to be durable for a design life of 75 to 100 years if the index test results meet or exceed what is defined in T925 as indicating good long-term durability. Index test results used for this purpose are as follows:

- For polyester (PET) geosynthetic products, number average molecular weight (Inherent Viscosity Method (ASTM D4603 and GRI Test Method GG8)), carboxyl end group content (CEG) (GRI Test Method GG7), and UV resistance (ASTM D4355).
- For polypropylene (PP) and high density polyethylene (HDPE), oxidation by oven aging (ENV ISO 13438:1999, Method A (PP) or B (HDPE)), and UV resistance (ASTM D4355).

The NTPEP test report provides the test results and the criteria used in T925 so that a comparison between the test results and the criteria can easily be made. Assuming the test results meet the criteria, the user of this data must, at that point, choose a value of $RF_D$ to use. T925 does provide some guidance on this issue, and recommends a default reduction factor for $RF_D$ that can be used for design. Per T925, a default value for $RF_D$ of 1.3 is recommended for typical situations, provided the environment is defined as nonaggressive (pH of 4.5 to 9, organic content is 1% or less, effective design temperature for site < 30° - see T925). For warmer climates, such as may occur in the southernmost tier of US states, a higher default reduction
factor for RF_D may be warranted. If the soil is considered to be chemically aggressive, special durability testing may be needed to determine an appropriate value for RF_D. See T925 for details.

With regard to polyolefins (i.e., PP and HDPE), the 1.3 default value is really aimed at PP geosynthetics, due to smaller thickness of ribs/fibers and relatively greater susceptibility to oxidation of PP relative to HDPE. A lower default reduction factor may be justified for HDPE geosynthetics, based on extensive very long-term performance observed for that material. For PET geosynthetics, the 1.3 default reduction factor is consistent with long-term research for environments with a pH as high as 9. If site soil conditions are known to be more neutral with regard to pH, a lower default reduction factor may be feasible. Some engineering judgment may need to be applied to determine an appropriate value of RF_D to use for design in consideration of the site temperature, chemical aggressiveness of the soil, and the polymer used in the geosynthetic.

Secant Creep Stiffness Data

The objective of this testing is to produce values of the 2% strain secant creep stiffness at 1000 hrs for potential use in geosynthetic stiffness based calculations such as is done using the K-Stiffness method for reinforced soil wall design (see WSDOT Geotechnical Design Manual) or for embankment base reinforcement design.

The data provided in the NTPEP test report typically includes a series of short-term ramp and hold tests at several load levels to establish a log-linear creep slope to enable extrapolation to the desired time (e.g., 1000 hours) and a few longer term creep tests to verify that the creep remains log-linear out to at least 1000 hrs. A couple of replicate tests are typically conducted for the full 1000 hours to verify reproducibility of the creep response at the desired 2% strain level. If the full 1000 hour tests verify that the creep data is log-linear throughout the 1000 hours and that the load level selected based on interpolation between the short-term ramp and hold tests closely achieves 2% strain at 1000 hrs, the testing verifies that short-term ramp and hold tests can be used for quality assurance purposes to verify 1000 hour 2% secant stiffness values in the future for the product line.

The NTPEP test report provides a summary of the 2% secant stiffness at 1000 hours for the products tested to characterize the product line. Interpolation to other products in the product line can usually be accomplished by plotting the stiffness values as a function of the ultimate strength of the material tested (T_{baseline}). See Figure 8 for an example.

Once the values for the creep stiffness are determined for each product in the product line, the stiffness values need to be adjusted to reflect the MARV or minimum value for the geosynthetic, so that a minimum stiffness that accounts for uncertainty in the strength of the material is determined, similar to what is done for the determination of T_{al}. Calculate the design stiffness value as follows:

\[
J_{design} = \frac{J \times T_{MARV}}{T_{baseline}}
\]  

(7)
where,

\( J_{\text{design}} \) = the low strain design stiffness value at the specified time (e.g., \( J_{\text{EOC}}, J_{\text{DL}}, \) etc.).

\( J_{\text{design}} \) accounts for the variability in the product tensile strength through the use of \( T_{\text{MARV}} \).

Figure 8. Creep stiffness as a function of \( T_{\text{baseline}} \).

If there is a desire to determine a secant stiffness at a different time or strain, the data provided in the test report can be used to accomplish that, at least within the range of time and strain tested. The equations for the log linear trend lines for the ramp and hold tests can be used to calculate strains at a given time and load level (or they can be estimated graphically), and the secant stiffness at the desired strain and time can be interpolated from those calculated values. Figures 9 and 10 illustrate the process to accomplish that. First, as shown in Figure 9, determine strains from each creep curve or its extrapolation using the trend lines established from regression analysis (the results of the regression will usually be provided in the NTPEP test report) at the desired time. Then plot each strain as a function of the calculated secant stiffness (see Figure 10), determined as follows:

\[
J = \frac{P \times T_{\text{baseline}}}{\varepsilon}
\]  

(8)

where,

\( J \) is the secant creep stiffness determined at the specified strain level and time,

\( P \) is the load level expressed as a % of \( T_{\text{baseline}} \),

\( T_{\text{baseline}} \) is the roll specific tensile strength of the sample used for the creep testing, and

\( \varepsilon \) is the strain in percent.

Once plotted, the creep stiffness value is determined as shown in Figure 10 at the selected strain level.
Figure 9. Strain versus time for short-term, low strain creep tests used to estimate secant stiffness.

Figure 10. Creep stiffness as a function of strain.

Other Data provided in the NTPEP Test Results

Detailed measurements of mass per unit area, and for geogrids, dimensions of grid aperture size, rib thickness, and node or junction thickness, and coating weight (for PET geogrids only, if
available) are provided in the NTPEP test report. This data can be used to visually verify whether or not the product received on a specific project is consistent with what was tested by NTPEP. This data is also used in some of the calculations to convert single rib test data to wide width test data (i.e., load per unit of specimen width), as well as to compare to what the manufacturer states regarding the product dimensions and unit weight for quality assurance purposes.

**Use of T$_{ult}$ Data from NTPEP Test Results**

Geosynthetic tensile test results per ASTM D4595 (geotextiles) or ASTM D6637 (geogrids) are conducted for multiple purposes with regard to NTPEP testing. This tensile testing is used to verify that the product tensile strength observed from independent testing is consistently greater than or equal to the manufacturer’s specified MARV or minimum value for the product. This data can be used by agencies as the basis for source approval or product qualification (e.g., for inclusion in the agency’s Qualified Products List). The NTPEP test results are not intended to replace agency directed or conducted project specific product acceptance or quality assurance T$_{ult}$ testing performed for the purpose of project specific acceptance or rejection of material shipped to a project site. In addition, the NTPEP T$_{ult}$ testing is used to determine the lot specific (baseline) tensile strength values for the rolls of product actually tested through the NTPEP testing program, for example to determine the values of RF$_{ID}$ and RF$_{CR}$ provided in the NTPEP test reports.

To understand how to specifically use the T$_{ult}$ data provided through the NTPEP testing, some key concepts must be explained first. The test result that is used to compare to the manufacturer’s specified value is the product acceptance/quality assurance test sample mean value, not the test values obtained from the individual specimens taken from the sample. The test sample is used to represent the entire roll of material. This is the reason the acronym MARV is used, in that “average” (i.e., “A” in the acronym) signifies that a mean value is used, and “roll” (i.e., “R” in the acronym) signifies that the unit sampled and tested is the roll of material. “Minimum” (i.e., “M” in the acronym) signifies that the “value” (i.e., “V” in the acronym) selected for comparison to quality assurance or acceptance test results obtained by others (e.g., agencies, owners, etc.) is a minimum value certified by the manufacturer for the product in question.

Note that the acronym “MARV” reflects the project specific perspective of the owner/agency with regard to their testing, not the perspective of the manufacturer with regard to quality control testing, as the owner/agency compares their mean value from the sample taken from a roll shipped to a project site to the manufacturer’s minimum certifiable value. To establish the MARV of a property for a specific product, the manufacturer uses the test results obtained from specimens taken and tested near the end of the product manufacturing process. The manufacturer’s quality control test results are used to establish the mean and standard deviation of the property, and those statistics are typically continuously updated as new quality control test results become available. The minimum value selected for the MARV is two standard deviations below the mean value obtained through the manufacturer quality control testing. Statistically, when comparing one test result distribution to another (i.e., the statistical distribution representing the manufacturer’s quality control testing and the distribution of the test results
from the roll sample obtained by the agency for acceptance or quality assurance purposes), the statistical parameters derived from both distributions (e.g., the mean) must have statistical significance. Hence the agency product acceptance/quality assurance testing must be a mean value for the sample taken from each roll, tested in accordance with the applicable ASTM or other test standard. Therefore, the manufacturer’s MARV must be compared to the mean test value for a sample obtained from a specific roll of material. Statistically, there is only a 2.5% chance that the agency project specific testing will have a sample mean test result that is below the manufacturer’s specified MARV.

Note that for most reinforcement products, manufacturers will provide a minimum $T_{ult}$ value for their products based on their production line quality control testing. The specified manufacturer minimum value is theoretically lower than the MARV in that there should be zero chance that agency project specific testing will have a mean roll sample test result that is less than the manufacturer specified minimum value. However, the minimum value is not determined statistically, but is simply the minimum value of all specimens tested by the manufacturer for quality control purposes.

Note that while $T_{ult}$ testing does not provide everything that could be desired to evaluate the quality of product shipped to a project site for reinforced soil construction purposes, it does provide an adequate index measure of the product quality. The full NTPEP product qualification and quality assurance testing will address the rest of the product quality issues that cannot be addressed by a simple short term test. The $T_{ult}$ testing, in combination with measuring product dimensions, unit weight, etc., may not recognize the occurrence of product processing changes, or possibly polymer source changes, should a product manufacturer make such changes between testing cycles (once every three years based on the current NTPEP work plan) without informing NTPEP of the change. The figure below illustrates the potential effect of polymer source or processing changes. Fortunately, the chance of this happening is relatively low, considering the frequency of NTPEP testing and the likelihood that at least some effect on the index properties of the product ($T_{ult}$, dimensional parameters, unit weight, etc.) is fairly likely.

![Figure 11. Time dependence of long-term geosynthetic strength and the conceptual effect of changes in $T_{ult}$ and processing changes.](image-url)
Concluding Remarks

This document provides a summary of the typical uses and interpretation of the data provided in NTPEP test reports for geosynthetic reinforcement. Once the individual reduction factors for installation damage, creep and durability have been determined, the long-term strength $T_{al}$ can be determined for each product. The $T_{al}$ values can then be used as the basis for product selection by contractors for geosynthetic reinforced walls or slopes, for example, using a Qualified Products List.