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Creep Tension Testing of Geosynthetics[*]

by

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[*] **GSI Members and Associate Members: A 50-slide power point presentation on this topic is available.**

Creep Tension Testing of Geosynthetics

Introduction and Overview

Creep is the tendency of a material to deform slowly and/or permanently under the influence of applied stress. We will focus on tension creep, but compression and even torsional creep are closely related phenomenon. In this regard, a simplified definition for tension creep is "strain of a material under constant application of a tensile stress". Unlike elastic behavior, creep deformation does not occur suddenly under the application of stress. Instead the strain accumulates as a result of sustained stress. Thus, creep is the time dependent strain of the stressed material under evaluation. The stages of creep deformation are shown plotted against time in Figure 1. Here "ε0" is the instantaneous strain associated with application of the applied stress. It has nothing to do with creep! This is followed by primary creep deformation which is essentially due to work hardening as the material adjusts to the applied stress. It is generally considered to be a viscoelastic phenomenon rather than creep-related mechanisms. Secondary, or steady-state creep, is most important and is the focus of the majority of creep studies, as in this white paper. Finally, tertiary creep exponentially increases with stress usually due to specimen necking and eventually leads to creep failure. Geosynthetics, being polymeric materials, follow along these same generalized trends. In this regard, Figure 2 shows data for geosynthetic materials illustrating secondary and tertiary creep behavior at low and high stress levels for different polymers. Note that the time axis is a log scale and thus instantaneous and primary stages are not included. It should also be noted that most creep stresses are normalized as percentages of the short term viscoelastic strength of the material.

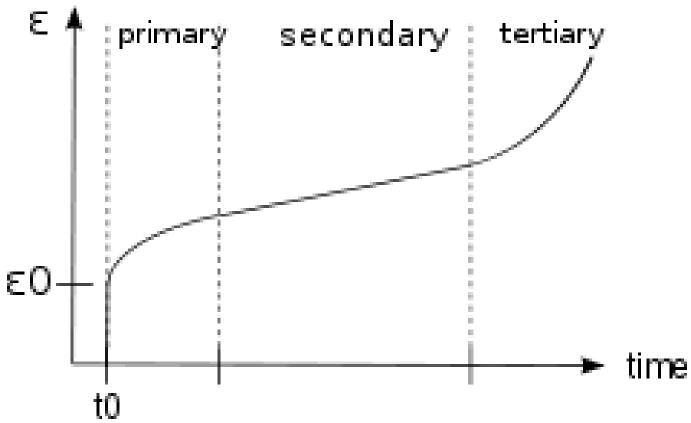
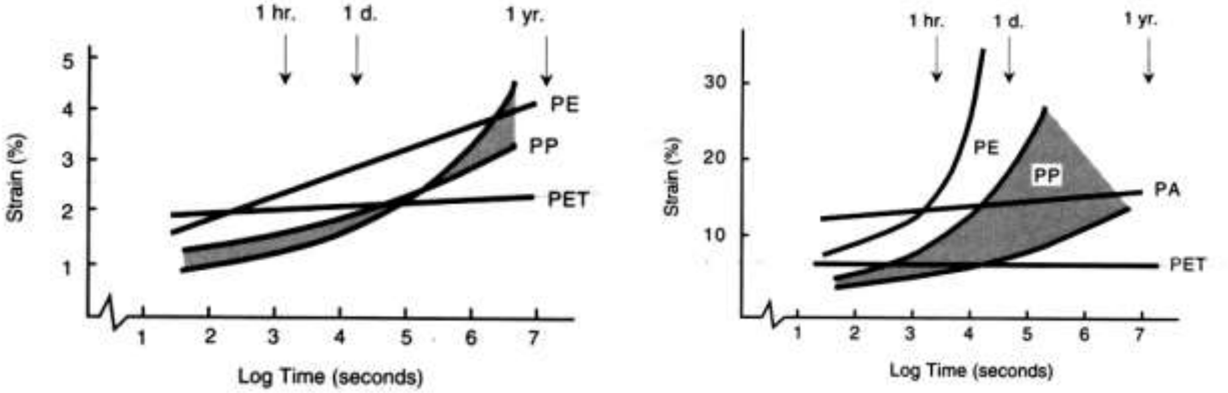


Figure 1 – Generalized stages of creep deformation (Wikipedia).



(a) Creep at 20% ultimate load (b) Creep at 60% ultimate load

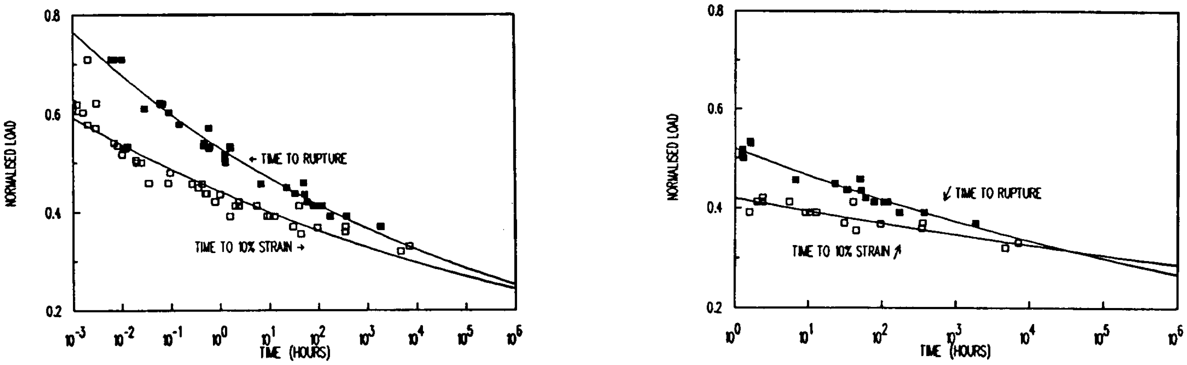
Figure 2 – Generalized creep response of various polymer types (den Hoedt, 1976).

Lastly, it should be mentioned that creep behavior of the most common polymeric resins falls into two categories based on the glass transition value (T_g) of the resin from which the geosynthetic material is made. Above this temperature the material is in a *rubbery state* and creep limits are generally restricted to a certain percent strain value, such as 10%. Below this temperature the material is in a *glassy state* and the material usually breaks at strains less than 10%. It is termed creep rupture. See Table 1 for typical geosynthetic resins and then Figure 3 for standard and creep rupture behavior out to 114 years which is the time frame for typical civil engineering structures.

Table 1 Glass Transition Temperatures of Common Polymers Used in Geosynthetics (Koerner, 2013)

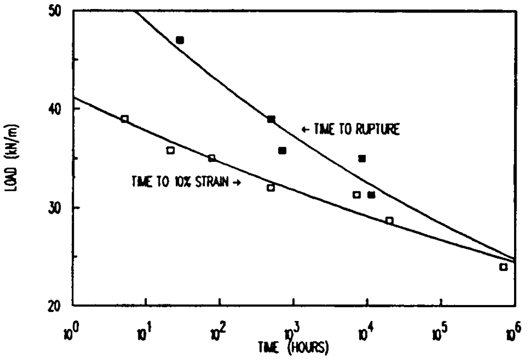
Resin Type	T_g-Value	Polymer State*	Controlling Mechanism*
HDPE	-80°C (-112°F)	rubbery	standard creep
PP	-10°C (14°F)	rubbery	standard creep
PET	75°C (170°F)	glassy	creep rupture
PVA	100°C (212°F)	glassy	creep rupture
PA	50°C (122°F)	glassy	creep rupture

*for 20°C (at higher temperatures; different conclusion)



(a) Creep strain is limiting

(b) Creep rupture is limiting



(c) It’s a tie!

Figure 3 – Creep strain versus creep rupture behaviors out to 10^6 hours (114 years) (Ingold, et al., 1994).

Tension Creep Testing of Geosynthetics

While all types of geosynthetic materials can be evaluated for their tension creep behavior it is the reinforcing materials (geotextiles, geogrids, geostraps and geoanchors) that are usually the target for such evaluation. This is the situation since (i) limiting strains are required for safety of the structure, and (ii) a specific reduction factor is necessary for the design process. McGown, et al. (1986) was pivotal in the original evaluation of polyethylene geogrids (focusing on limiting strains) followed by Voskamp and Risseeuw (1988) on polyester fibers and fabrics (focusing on creep rupture). Eventually, and after many published and unpublished studies, two parallel standardized test methods were developed, namely ASTM D5262 and ISO 13431.

In both standards the test specimen is firmly gripped at its ends and then stressed mechanically or hydraulically (as in Figure 4). There is no lateral confinement against the test specimens since Wilson-Fahmy, et al. (1993) have shown that when uncoupled from the lateral confinement there is no beneficial or detrimental effect. Deformations during creep testing are read by grip separation or alternatively by LVDT's or lazer's and are then converted to engineering strain using the original gauge separation distance. Data sets of instantaneous strain versus time are then plotted as shown in Figure 5 for different stress levels.

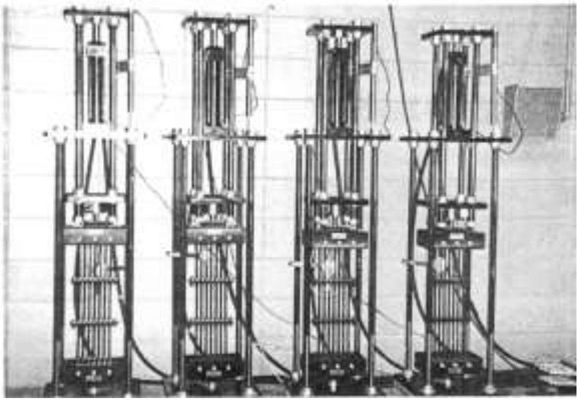
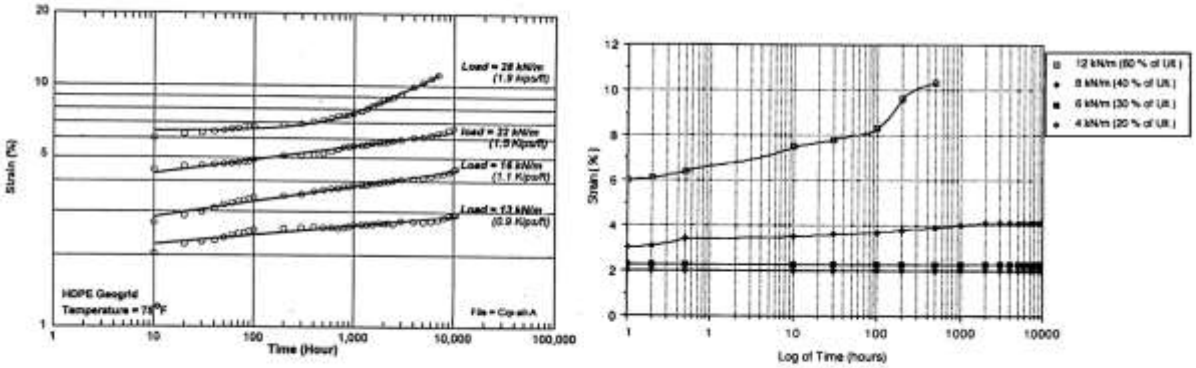


Figure 4 – Standard creep testing of geogrids at different stress levels
(Farrag, et al., 1997, 1998).



(a) HDPE Geogrids (Farrag, et al. (1997) (b) PET Yarns (ASTM D5262)

Figure 5 – Creep strain results under conventional testing at room temperature for 10,000 hour durations per load increment.

Inasmuch as the previous data is tedious and time-consuming to obtain it is also subjective in order to obtain a limiting stress level for a critical structure like a reinforced wall, slope or foundation. For example, even for the lowest stress level of the geogrid shown in Figure 5a the strain is increasing with time signifying non-equilibrium of the test specimen at least within the 10,000 hours of test time. Conversely, the data shown in Figure 5b shows equilibrium at 30% of ultimate short-term load which, in the context of a creep reduction factor for design purposes, is taken as its inverse value 1/0.30 = 3.3 and used in the following equation (Koerner, 2012).

$$T_{allow} = T_{LTDS} = \frac{T_{ult}}{RF_{CR} \times RF_{ID} \times RF_{ED}}$$

where

T_{allow} = allowable design strength (also called)

T_{LTDS} = long term design strength

T_{ult} = strength of the as-manufactured product

RF_{CR} = reduction factor for creep

RF_{ID} = reduction factor for installation change

RF_{ED} = reduction factor for environmental degradation

It should be mentioned that in the context of currently manufactured reinforcement geogrids the commonly used reduction factors are much lower than that indicated above. For example, using data published in the Specifiers Guide (2013) the following is the data range for the three different geogrid group types.

- integral HDPE types = 2.60 to 2.70
- woven or knit PET types = 1.40 to 1.58
- rod or strap PET types = 1.40 to 1.45

Most significant in the data shown in Figure 5 is that 10,000 hour (1.14 years) data needs two orders of extrapolation to reach 100-year lifetime prediction and some professional groups (like ASCE) only allow for one order of magnitude extrapolation. This infers that the creep testing itself should be maintained for 100,000 hours (11.4 years) which is considered by most to be unwieldy in the context of a specific material or project. In turn, such long testing times suggest some type of accelerated testing protocol which is currently satisfied using the technique of testing at several elevated temperatures. It is generally called “time-temperature superposition”, or simply TTS.

Accelerated Creep Testing Using Elevated Temperatures

It is generally (perhaps even universally) accepted by materials scientists and engineers that temperature plays a pivotal role in accelerating the performance of materials, including polymer products such as geosynthetics. Thus, at elevated temperatures beyond the typical 20°C stated in most test standards, all degradation mechanisms will increase proportionately. These mechanisms include the following in which elevated temperatures can be considered as being the catalyst for accelerated creep to occur.

- hydrolysis
- ultraviolet light
- chemical
- radioactive
- biological
- oxidation

Simplistically stated, the higher the testing temperature the shorter the testing time, as well as the enhanced time projection of creep strain that can be achieved. For the creep testing setup as shown in Figure 4, one needs to place the assembly (at least the test specimen itself) in an environmental chamber under controlled temperature as shown in Figure 6.

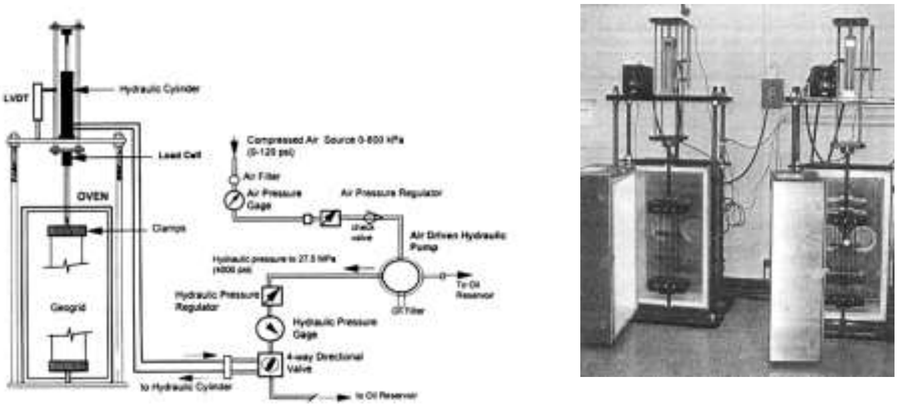


Figure 6 – Schematic diagram of hydraulic creep and photograph of several creep frames with test specimens placed within environmental chambers (Farrag, 1997, 1998).

By setting each environmental chamber at higher temperatures (say T_1 at 20°C, then T_2, T_3, T_4, etc. at 10°C successfully higher temperatures) creep strain curves for equivalent times are successively higher in their magnitudes. This is hypotehtically shown by bold lines in Figure 7. Now by *horizontally shifting* the elevated temperature curves with respect to the reference temperature curve, a *master curve* is obtained which represents the creep strain out several orders of magnitude beyond each individual test's duration..

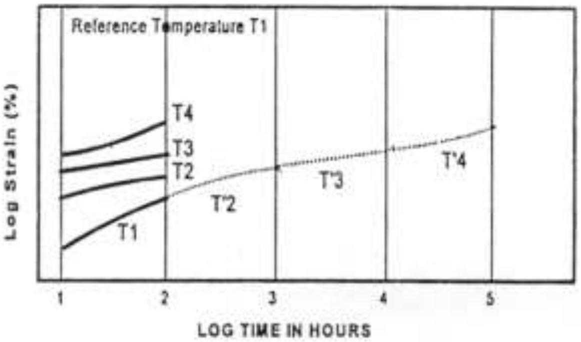
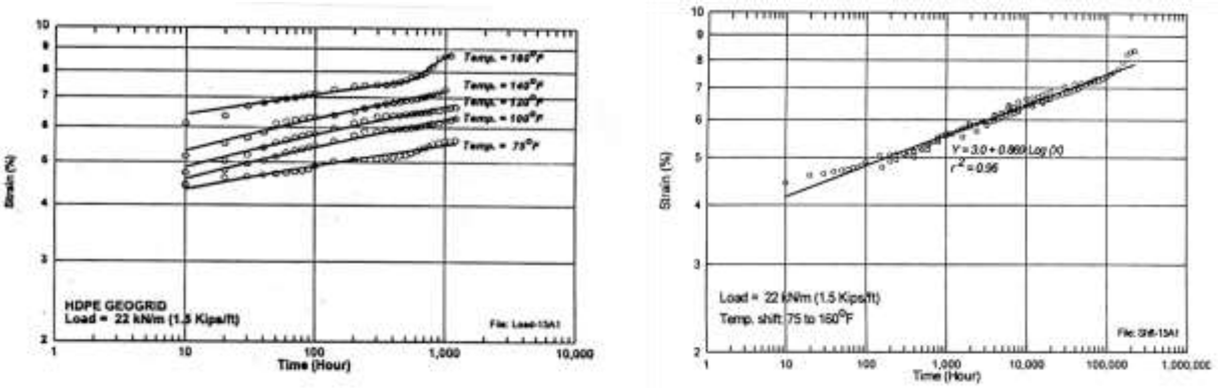


Figure 7 – Generation of a "master-curve" by horizontal shifting.

To illustrate actual data, Farrig (1997, 1998) has evaluated the same type of geogrid at five successively higher temperatures, see Figure 8a. Each test was stressed at 22 kN/m and maintained for 1000 hours. The data indicates that the highest temperature evaluated brought the geogrid from secondary into tertiary creep. By horizontal shifting of the data, as in Figure 7b, this can be clearly seen in that the geogrid's creep strain is about 7.5% at 200,000 hours (23 years) at the initial reference temperature of 24°C (75°F) before tertiary strains are indicated.



(a) Creep strains in 1000-h tests at 22 kN/m

(b) Master curve using horizontal shifting

Figure 8 – Elevated creep testing results along with horizontally shifted master curve, after Farrag (1997, 1998).

Accelerated Creep Using "Stepped Isothermal Method"

There are two shortcomings of the previously described TTS method for creep evaluation. The *operational one* is that multiple environmental chambers are necessary to provide for simultaneous temperature evaluations. The *fundamental one* is that different (albeit hopefully representative) test specimens are needed for each temperature evaluated.* In geosynthetic testing both of the above drawbacks have been eliminated by using the stepped isothermal method, or "SIM". The method was developed by TRI Environmental Laboratories

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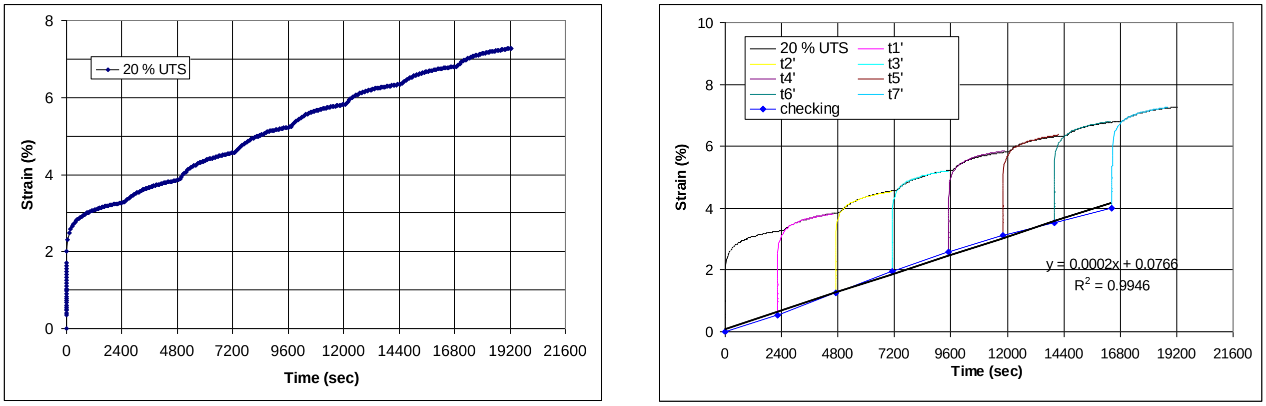
*This drawback in triaxial soils testing was recognized by Professor Robert Kondner of Northwestern University in the 1970's who devised the concept of hyperbolic testing for shear strength on a single soil test specimen.

in Austin, Texas by Scott Thornton and his colleagues (Thornton, Allen, Thomas and Sandri, 1998). It was later substantiated by Greenwood and Voskamp (2002) and eventually adopted as a test standard first by GRI and eventually by ASTM as standard D6992.

The testing concept does indeed use elevated temperature steps as in TTS but now within a single environmental chamber using a single test speicmen. It will be presented in a much more procedural manner than that presented in the previous section. Yeo and Hsuan (2008) have used the SIM procedure on a single rib of an HDPE geogrid at 20% ultimate stength and conducted eight elevated temperature steps holding each for 2400 sec. *Thus the entire test took only 5.3 hours!* Figure 9 presents the data and its analysis in six sequential graphs. They are described as follows;

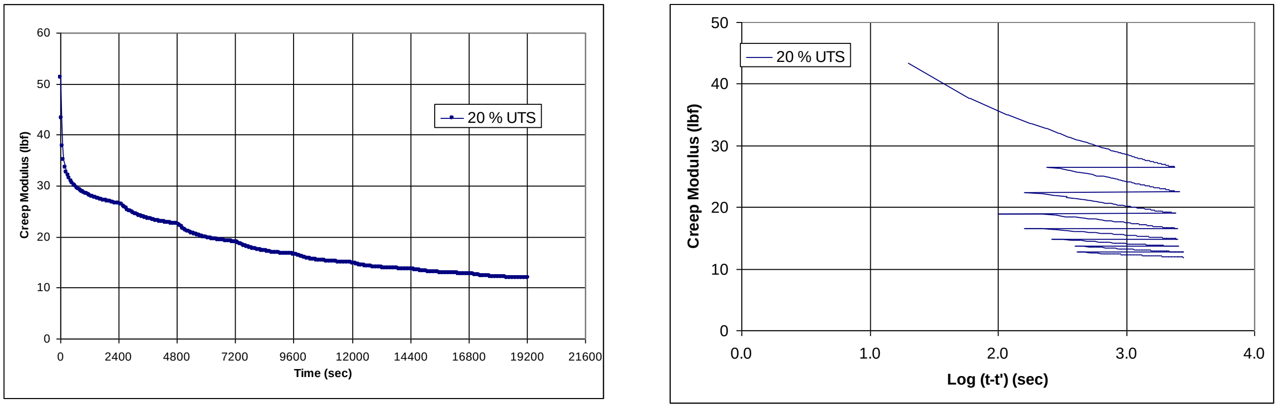
Fig. 9a	The raw data of measured strain versus time is presented for each temperature step
Fig. 9b	The projected time back to the original baseline for each temperature step after the initial one is presented. This requires a computer program with some obvious assumptions.
Fig. 9c	The creep modulus (inverse of strain) for each temperature step is calculated and graphed accordingly.
Fig. 9d	The modulus data for each temperature step is cascaded onto the original temperature step of 20°C.
Fig. 9e	Horizontal shifting of modulii for each temperature step is conducted in a head-to-tail manner so as to produce a smooth curve.
Fig. 9f	The master curve of modulii values is inverted back to strain values for the final predicted behavior in terms of strain versus time. Note that at 10^{10} seconds (316

years) the predicted strain is 6.8% from this single SIM test which took 5.3 hours of laboratory test time… the method is simply "awesome"!



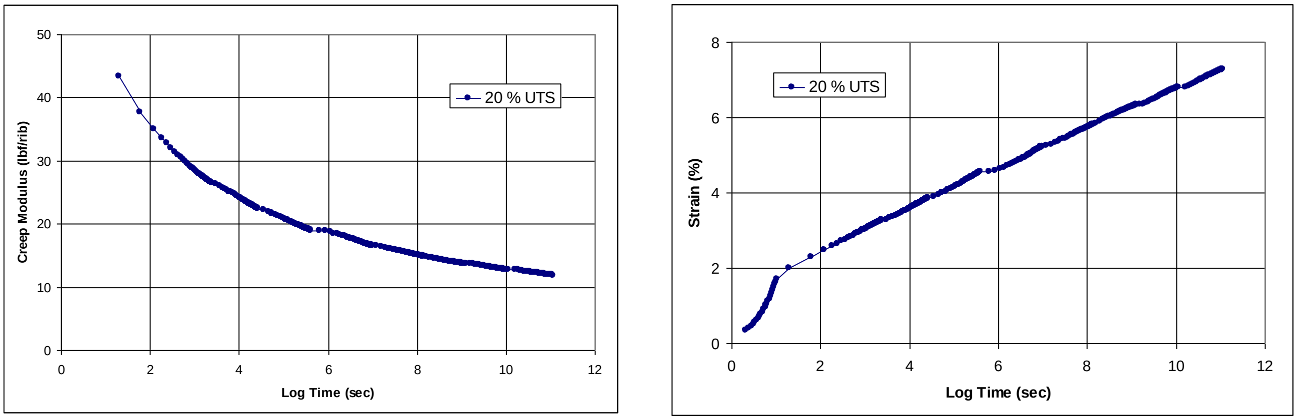
(a) Raw cascading strain data using single test specimen

(b) "Tails" added to strain data to establish incremental baseline



(c) Strain data converted to modulus

(d) Modulus data plotted on semi-log axis ready for horizontal shifting



(e) Modulus data shifted horizontally (head-to-tail horizontal shifting)

(f) Modulus data converted back to strain: Note at 10^{10} sec (316 yr) the strain is 6.8%

Figure 9 – Graphic illustration of the data reduction and analysis generated by stepped isothermal method (SIM) testing (Yeo and Hsuan, 2008).

It is important in any advance from earlier established procedures (as in standard creep testing) to compare different newer procedures to one another. This has been done in comparing the TTS method with the SIM method on the same type of geogrid. See Figure 10 for such a comparison in which the agreement is seen to be excellent; i.e., 6.4% versus 6.8% strain at 10^{10} sec (316 years).

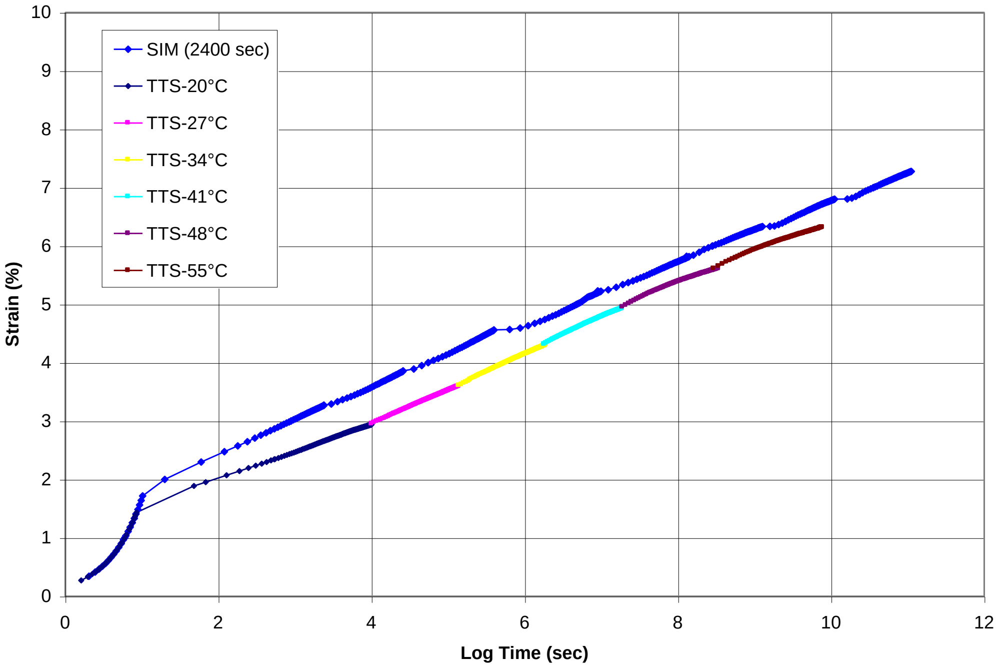


Figure 10 – Comparison of TSS and SIM results indicating excellent agreement (Yeo and Hsuan, 2008).

Summary and Conclusions

This white paper is focused on the tension creep testing and data reduction procedures for geosynthetics particularly when they are used in reinforcement applications, i.e., walls, slopes, foundations, etc. Its importance is in the obtaining of a predictive long-term strain value as well as the formulation of a creep reduction factor for design. The white paper has addressed three different creep testing and data analysis methods. They are given in Table 2 with selected advantages and disadvantages. The first (traditional creep) began for geosynthetics in the late 1980's, the second (elevated temperature testing) begain the late 1990's and the third (stepped isothermal method) began somewhat thereafter.

Table 2 – Summary of Creep Methods Addressed in this White Paper

Method	Concept	Advantages	Disadvantages
Traditional Creep Testing	Apply stress and measure strain over an extended time	• Straightforward • Inexpensive • No data assumptions	• Long time required • Needs controlled laboratory environment
Time-Temperature-Superposition	Apply stress and measure strain at several elevated temperatures in separate chambers	• Reduces testing time • Uses TSS concept • Avoids direct extrapolation	• Needs environmental chambers for each temperature • Specimen variation is a concern
Stepped Isothermal Method	Apply stress and measure strain while increasing temperature in steps in a single chamber	• Greatly reduces testing time • Uses TSS concept • Avoids direct extrapolation • Uses single test specimen	• Needs a single environmental chamber • Requires computational algorithms • Needs full user acceptance

While it is known that some manufacturers continue their traditional creep testing (one company for over 30-years), the geosynthetics industry has become reasonably comfortable with elevated temperature testing largely based on greatly reduced testing times. Time-temperature-superposition (TTS) testing is used in most materials testing situations, including the polymer industry as a whole. Creep data which took years to obtain can now be generated in 10,000 hours (1.14 years) or less. Of course, multiple test/incubation chambers are needed and costs increase commensurably. The newest variation of TTS is to step the temperature increments in a single environmental chamber which contains the entire test specimen and gripping assembly. The method is called the stepped isothermal method (SIM) and it can produce results in a day or less. Not only is the extremely short time an advantage, the method uses a single test specimen throughout. Thus specimen variability is eliminated. Having such tremendous advantages it is surprising that so few laboratories provide SIM testing services. For example, only three accelerated laboratories in the Geosynthetic Accreditation Institute's-Laboratory Accreditation Program provide such services. Product development and modifications can certainly benefit from the greatly reduced testing time so as to provide rapid and timely results. Likewise, geosynthetic reinforcement designers (in need of creep reduction factors) and owners and regulators of geosynthetic reinforced structures (in need of creep lifetime estimates) are greatly aided in their decision-making processes by having such information available in a timely fashion.

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