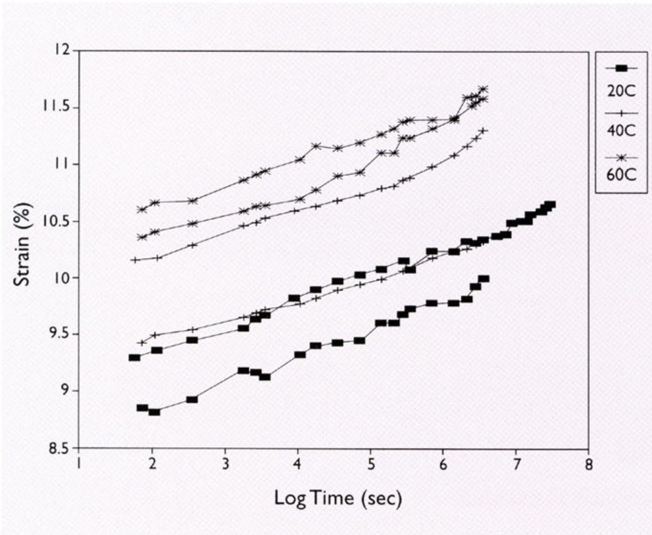

Figure 1. Typical creep-curve-replicate set at temperatures of 20°, 30° and 40° C. Note variation in "initial creep strain" between "identical" specimens (after Thornton et al. 1998b).

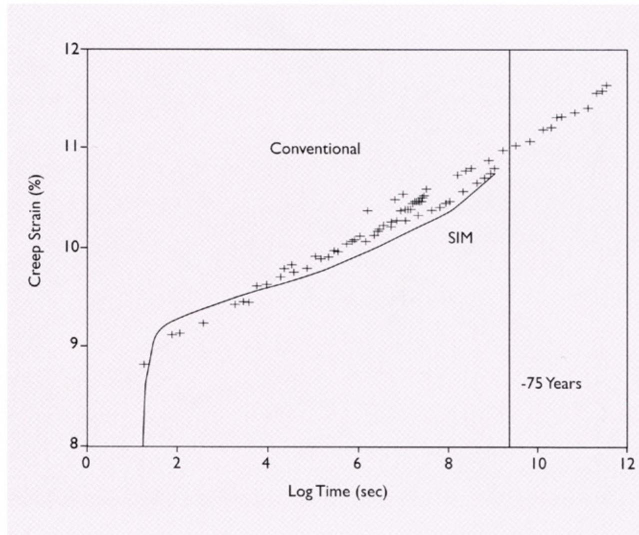

Figure 2. Use of TTS principals and "shifting" of single stress curves (56%) produced in Figure 1 provide an extended strain-time behavior line—note scatter in data and relative curve roughness. The results of SIM testing at 56% strain are depicted by the solid line. Conventional data represent 15,000 test hours vs. 14 hours of SIM testing (after Thornton et al. 1998b).

Measuring geosynthetic creep: three methods

A quick review of the pluses and minuses of conventional creep, time-temperature superposition and a new approach—the stepped isothermal method.

By Dean Sandri, J. Scott Thornton and Rich Sack

GEOSYNTHETICS OFTEN ARE USED IN SUCH mechanically-stabilized earth (MSE) structures as segmental retaining walls, steepened slopes and embankments over weak foundations. In all of these applications, reinforcement geosynthetics may be required to endure exposure to high tensile stresses for long periods of time—typically 75-plus years. The load-strain-with-time behavior (creep) of the reinforcement geosynthetic is a significant design consideration, particularly because these materials are called upon to perform for such long periods.

Users of polymeric (extensible) soil reinforcements rely on accurate determination of the load-strain behavior with time. The creep behavior of polymeric reinforcement has been determined conventionally via simple creep-testing protocols (ASTM D 5262). These protocols require that the load-strain behavior be monitored over time. Long-term (75-plus year) predictive behavior typically requires constant ambient-temperature creep testing for long experimental time periods (more than 7.5 years). Linear extrapolations, limited to one time decade (e.g., from 7.5 to 75 years) of conventional-creep test data, work well for the polymers (polypropylene, polyethylene and polyester) commonly employed in current reinforcement geosynthetics, provided that load levels are well below those that will lead to creep rupture.

Load-strain behavior can be predicted within condensed time frames by imposing such elevated temperature and superposition principals as Arrhenius or Williams-Landell-Ferry (WLF) modeling (ASTM D 2990, D 5262, Ferry 1980, Thornton et al. 1999a).

Time-temperature-superposition (TTS) principals can help predict material behavior beyond the the time periods considered in the laboratory at constant ambient temperature.

TTS principals work relatively well for polyolefins that exhibit large changes in load-strain behavior with only moderate temperature changes. However, these concepts are considered relatively ineffective for polyester, which exhibits only modest changes in strain behavior with temperature changes.

The Stepped Isothermal Method (SIM) was developed recently to measure load-strain behavior (Thornton et al. 1997, 1998a, 1998b, 1999a, 1999b). This method employs TTS modeling with refined measurement of temperature, load and strain, along with minimized sample-to-sample variation. Such refinements provide results showing recognizable changes in load-strain behavior with relatively minor changes in temperature. As a result, SIM is applicable particularly to polyester and also is valid for polypropylene and polyethylene.

Each of the above methods of determining polymeric-soil-reinforcement load-strain behavior has pros and cons that should be considered by the user before the test is accepted or required. Some of these considerations are summarized below.

Conventional creep

Conventional creep testing typically is conducted in accordance with ASTM D 5262, which requires that a fixed-end geosynthetic specimen be subjected to a constant load. The test method measures strain as a function of time. Loading times of 10,000 hours (approximately 1.1 years) generally are recommended. Results are plotted as strain (ordinate) vs. log time (abscissa) and the onset of creep (transition from plastic strain to creep strain) is determined from correlations with ASTM D 4595 test results. (See **Figure 1**.)

It is important to note that locating the initiation point of the creep curve (the transition region in which plastic strains caused by short-term load application change to time-dependent creep strains) is difficult and somewhat arbitrary. For conventional-creep-test results, the initial creep strain typically is based upon the strain developed in the short-term (ASTM D 4595) test at a load that corresponds to the one employed in the long-term process. However, this practice is not conservative (Thornton et al. 1999).

Advantages

- **Common set-up**

The conventional creep-testing apparatus consists of a relatively simple loading frame that facilitates dead-weight loading or provides a mechanical lever capable of applying a specific load. A strain-measuring system is required to record measured extension of the geosynthetic specimen with time. Creep-loading frames typically are uncomplicated and relatively inexpensive to fabricate and operate. These apparatuses also are available readily, allowing many service providers to perform the test.

- **Well-established testing protocol**

Conventional creep-testing protocols are well documented by ASTM (D 5262) and international standards organizations. The acceptance level and international recognition of conventional-creep-testing protocols make the test relatively common in the marketplace.

Disadvantages

- **Little information from a single test**

A single test provides strain-time information for one loading increment, one temperature and only for the period of time for which the test is performed. While it is common to interpolate between methods that bracket the load, time and temperatures actually tested, little information is available on how the material may behave at levels beyond those assessed.

- **Identification of creep onset is somewhat arbitrary**

In conventional-creep testing protocols, ASTM D 4595 or another similar short-term test is utilized to predict the onset of strain. However, this approach may be unreliable since the loading rate and mechanism differ between the short-term and long-term tests. These variables also are less controlled in conventional-creep testing. This deviation can be significant, as shifts in the initial-strain magnitude are carried through the entire test, affecting the total strain values upon which long-term design values are based.

- **Long testing duration needed for meaningful results**

Current practice requires that extrapolation of physical test results obtained by conventional creep testing be limited to about one log cycle on the time scale. Products designed for service lives of 75-plus years would require 7.5 years of data gathered at ambient temperature in order to determine performance for the required service life. This test duration is impractical and typically time- and cost-prohibitive.

- **Test set-up occupies large area**

The loading frames typically used for conventional creep tests occupy a relatively large footprint. This, along with the number of frames required to develop meaningful test sequences, results in large laboratory space requirements and, consequently, high test costs.

- **Difficult to move**

Ongoing tests are difficult to relocate without disturbing the specimen. Likewise, tests conducted in areas subject to vibration or disturbance risk being affected by external, non-creep-related factors. Even minor vibrations can affect adversely the shape of the strain-time curve. And if disturbances occur near the rupture phase, they can rupture specimens prematurely. In any event, vibrations create unnatural strain in geosynthetic specimens.

Time-temperature superposition (TTS)

Time-temperature-superposition principals utilize the concept that increasing temperature accelerates the creep rate, thus reducing the time required for a given amount of creep to occur. By combining several sets of data developed at increasing temperatures, the resulting creep curves can be graphically or mathematically "shifted" relative to the reference temperature until a smooth curve is obtained. Shifting several elevated temperature curves leads to a smooth master curve at a pre-determined reference temperature. The resulting master curve can be used subsequently to predict the strain-time behavior at a particular reference temperature for time periods far in excess of those used to develop the laboratory data.

Advantages

- **Accelerated creep response**

Elevated temperatures cause creep responses within reasonable laboratory time frames. Periods of minutes to days, instead of the years or decades usually required, are utilized to predict ambient-temperature responses. Hence, utilization of TTS principals over relatively short laboratory time frames can develop predictive creep responses for times far in excess of those required for civil-engineering projects.

• **Standard protocol**
TTS principals and evaluation procedures are well understood and documented in such standard protocols as ASTM D 2990. Using such standards ensures maximum repeatability and uniform results.

Disadvantages

• **Time**
The standards employed in the current marketplace still require baseline tests to be run for 1-plus years at the "reference" temperature. Tests that require such long periods to complete typically are expensive and not conducive to most ongoing civil-engineering projects.

• **Specimen-to-specimen variation**
TTS requires that a new specimen be used for each sample replicate. This variation causes scatter in the data used to develop families of elevated-temperature curves for a given loading condition, which may be sufficient to mask the shift factors of some polymer types. This is true especially for materials that are not highly temperature sensitive, such as polyester.

Polyolefins respond better to conventional TTS due to their temperature-strain dependence. However, variation remains a problem that can be overcome only with numerous replicates.

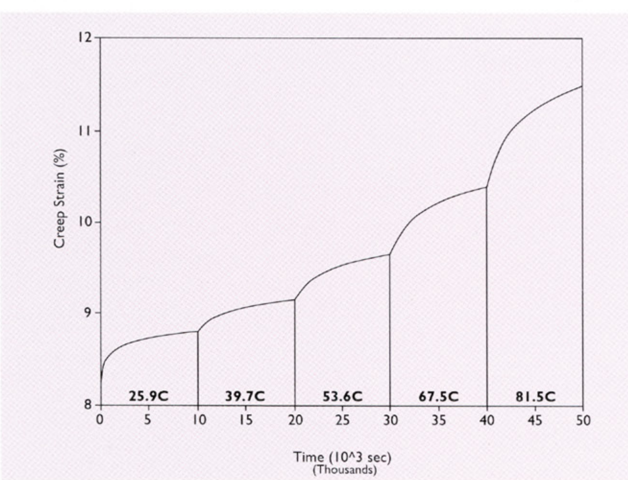

Figure 3. Raw creep strain vs. time data using SIM. Note the creep responses to the stepped-temperature program.

• **Shift factor uncertainty**
Test personnel determine shift factors by superimposing time-strain curves developed from testing at various temperatures. Because the data quality is dependent on sample-to-sample variation and other testing variability, curves are often less than perfect and hence curve-fitting (shifting) is substantially dependent on visual judgement. The quality of the finished curves affects the visual curve-fitting process and shift factors that are developed.

• **Space constraints**
Like conventional creep testing, TTS apparatus typically are relatively large and require large physical areas. Insulated chambers (or rooms) must be utilized to meet the temperature-control demands of elevated-temperature work. These facilities typically require even more space than those in which ambient-temperature testing is conducted.

• **High cost**
A statistically significant number of replicates must be tested to account for specimen-to-specimen variation. This process is prohibitively expensive and time-consuming.

Stepped Isothermal Method (SIM)

SIM utilizes a combination of conventional-creep-testing and TTS principals. Like its alternatives, SIM employs constant load-testing methods to develop time-strain responses. It also utilizes a series of elevated-temperature steps to accelerate creep response (See **Figure 3**) and curve-shifting to develop a reference mastercurve (**Figure 4**).

SIM departs from conventional creep and TTS in that it employs one sample that is subjected to a constant load while being exposed to several increasing temperature steps. Baseline-strength data is measured with tensile-clamping equipment identical to that employed for conventional-creep loading. Temperatures and loads are monitored closely during testing.

Use of a single specimen eliminates the sample-to-sample variability experienced with TTS, provides improved data quality (smoother, more precise curves), and minimizes the uncertainty of determining shift factors (**Figure 2**). Most significantly, SIM effectively utilizes comparatively small temperature steps and short time-dwells in contrast with conventional TTS.

Advantages

• **Short time duration**
Typically, a series of SIM tests only requires days to complete, rather than weeks, months or years. This short time period makes SIM an attractive alternative for quality-assurance monitoring, product development or other strain-behavior verification work.

• **Single specimen tests**
Specimen-to-specimen variability is eliminated with a single specimen used to develop data for several temperature increments. This, in turn, improves curve definition and shift-factor accuracy.

• **Onset of creep is defined easily**
The transition from plastic to creep strain is defined easily, as initial loads and strains are monitored continuously. Loading for creep testing is conducted at identical rates and with the same equipment used to develop characteristic short-term strengths.

Disadvantages

• **New test**
SIM is a relatively new test that currently is only being actively performed and marketed by one U.S. laboratory. Because it is new, few in our industry understand or appreciate its significance. As a result, acceptance will be limited until such time as SIM is adopted into national standards.

• **Expensive equipment required**
Temperature and loading must be controlled precisely in order to successfully perform SIM testing. Equipment requirements include highly sensitive strain-measuring devices, an environmental chamber capable of quickly and precisely changing temperatures, clamps that can handle high loads without damaging the specimen or allowing it to slip, etc. Such equipment is highly specialized and significantly more precise than that required for TTS or creep, and also is quite expensive.

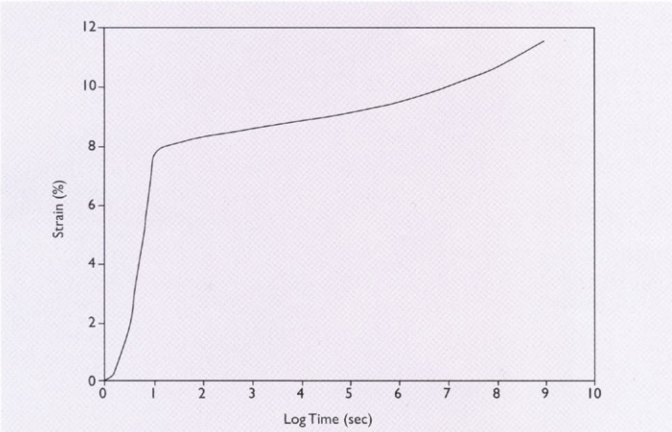

Figure 4. Master creep strain vs log time curve for a single loading stress. This curve is the result of rescaling and shifting the raw data of Figure 3 using SIM. The curve is derived from simply connecting the (approximate) 2000 data points. No curve-fitting has been employed.

Applications

OK, so we have three ways of testing the strain-time behavior under load of geosynthetic reinforcements. Who cares? We all should. Whether you're a manufacturer, an owner/engineer/user or a laboratory, SIM provides a useful tool to meet our needs.

Manufacturer's perspective

SIM can provide quick feedback on the behavior of new products, thus speeding their introduction. The test can be used to develop load-temperature-strain behavior for unique applications typically encountered in non-civil-engineering markets. SIM also can be used to supplement conventional data not readily or practically available via conventional testing procedures.

While SIM is a useful tool, the conventional creep and TTS methods are more generally accepted by regulators. There is a limited risk that the high quality, state-of-the-art results from this non-traditional technique will be set aside in favor of less precise, but more frequently referenced, traditionally developed data.

User's or owner's perspective

Geosynthetic-reinforcement-material creep currently is qualified by conventional creep or TTS methods. Acceptance at the job site typically is based on certificates of compliance that include current lot-test results for index properties not directly related to long-term performance. Relevant performance properties, such as load-time-strain relationships, are certified based on test series that were conducted on materials produced months or years before—materials that may not characterize those delivered to the site.

Unlike conventional creep testing, SIM provides a potentially viable QA tool that can be used to ensure that materials received on a job site possess the load-strain-time properties specified or required by the design. Such QA testing can be accomplished at relatively minimal cost and in time periods that work with civil-engineering-project schedules.

Academic/laboratory perspective

SIM opens up many new testing opportunities that have heretofore been time- and cost-prohibitive. Some research- and design-related questions that might be investigated conveniently with SIM include the synergistic effects of installation damage and creep, durability and creep, or the effects of process changes on product performance. Thus, SIM-type procedures make other research efforts possible.

Conclusions

Conventional creep measurement, TTS and SIM all have their place in the current geosynthetic marketplace. While each method possesses characteristics that are particularly desirable for some applications, conventional creep and TTS remain the methods of choice for widely accepted performance-evaluation methods. SIM appears to provide significant cost and time benefits and is gaining acceptance within the regulatory environment. Further, SIM shows great promise in QA, new product development and other areas, such as research on synergistic effects.

Ongoing development of load-strain-time standards within ASTM, the Geosynthetic Research Institute (GRI), State Departments of Transportation and international standards groups will increase acceptance of procedures that determine the long-term behavior of reinforcement. Until such time as the standards regularly accepted by civil engineers include procedures used to identify the "creep" behavior of geosynthetic reinforcement, awareness must be raised by information sharing and educational campaigns. GFR

Dean Sandri, P.E., is TC Mirafi's Western Region sales manager, based in Lake Forest, Calif. **J. Scott Thornton, Ph.D.**, is chairman and president of Texas Research International Inc., Austin, Texas. **Rich Sack** is Western regional engineer for Pendergrass, Ga.-based TC Mirafi.

References

ASTM D 2990. "Tensile Compressive and Flexural Creep and Creep Rupture of Plastics." West Conshohocken, Pa.: American Society for Testing Materials.

ASTM D 5262. "Standard Test Method for Evaluating the Unconfined Tension Creep Behavior of Geosynthetics." West Conshohocken, Pa.: American Society for Testing Materials.

ASTM D 4595. "Standard Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method." West Conshohocken, Pa.: American Society for Testing Materials.

Ferry, J. D. 1980. *Viscoelastic Properties of Polymers*, 3rd Ed. New York: John Wiley and Sons.

Thornton, J.S., Allen, S.R. and R.W. Thomas. 1997. Approaches for the Prediction of Long-Term Viscoelastic Properties of Geosynthetics from Short-Term Tests. *Geosynthetics '97 Conference Proceedings*. St. Paul, Minn.: IFAI. pp 277-291.

Thornton, J S, Allen, S.R., Thomas, R.W. and D. Sandri. 1998. The Stepped Isothermal Method for Time-Temperature Superposition and its Application to Creep Data on Polyester Yarn. *Sixth International Conference on Geosynthetics Proceedings*. Roseville, Minn.: IFAI. pp. 699–706.

Thornton, J.S., Paulson, J.N. and D. Sandri. 1998. Conventional and Stepped Isothermal Methods for Characterizing Long-Term Creep-Strength of Polyester Geogrids. *Sixth International Conference on Geosynthetics Proceedings*. Roseville, Minn.: IFAI. pp 691–698.

Thornton, J.S. and D. Sandri. 1999. Introducing the Stepped Isothermal Method: Part One. *GFR*. (vol. 17, no. 3, April). pp. 16–20.

Thornton, J.S., Sprague, C.J., Klompmaker, J. and D.B. Wedding. 1999. The Relationship of Creep Curves to Rapid Loading Stress-Strain Curves for Polyester Geogrids. *Geosynthetics '99 Conference Proceedings*. Roseville, Minn.: IFAI. pp. 375–744.