Variability in curve shifting when applying the Stepped Isothermal Method

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ABSTRACT: The Stepped Isothermal Method (SIM) is widely used for predicting creep strain and time to rupture of geosynthetic products. Tensile and more recently compressive SIM testing have been the subject of ASTM standards. Cobham ERA has already published a comparison between the predictions of SIM tests and the results of 15 year creep tests which in general vindicate the SIM predictions. However, so far there has been no comprehensive evaluation of the reproducibility of the method. The overall principle of curve shifting is well defined: the shift factors are optimised such that the sections of creep curve abut one another with minimum change of gradient. However, since the procedure is operator dependent there can be some variations in the way this is obtained. The various shifts can also be performed by computer programme. This paper details the different potential sources of variability and their relative importance in the overall uncertainty of SIM tests.

1 INTRODUCTION

The Stepped Isothermal Method (SIM) was developed at the end of the 1990's to predict the creep behaviour of geosynthetics. Based on the time-temperature superposition (TTS) principle, it was first used as a test method to characterise tensile creep properties of yarns, geotextiles and geogrids (Thornton et al. 1998a, Thornton et al. 1998b). More recently, the method has also been adapted to test compressive creep properties of drainage materials (Narejo & Allen 2004, Zanzinger 2008, Greenwood & Young 2008). Both methods are the subject of ASTM standards (respectively D 6992 and D 7361 for tensile and compressive SIM).

The method consists of applying steps of increasing temperatures on a sample under load. Following data analysis, it enables the creep behaviour of the material for durations up to several hundred years to be predicted, based on a 24 hour test. Its advantage over conventional TTS tests is that the creep curves are based on tests performed on single specimens, whereas with conventional TTS tests one specimen is tested for each temperature used. Therefore SIM requires less time for setting up and running tests and eliminates the error related to sample-to-sample variations. Comparison between the predictions of SIM tests and the results of 15 year creep tests published by Cobham ERA showed good correlations between both and thereby validates use of SIM results (Greenwood et al. 2004).

One aspect of the method which has not yet been fully investigated is its variability. This variability arises from:

- Accuracy of the measuring equipment,
- Repeatability of the test method, including variations in the material
- Choice of temperature shifting method
- Differences between operators in evaluating the results

This paper investigates the variability in predicted strain as a function of these contributions.

2 MATERIALS & TEST PROCEDURES

Examples of both compressive SIM and tensile SIM will be discussed in this paper.

Compressive SIM tests were performed on a polyethylene cuspated sheath for drainage applications. Specimens consisted of two square 100mm^2 samples stacked one on top of the other and separated by a thin aluminum plate. The tests were carried out following the procedure described in ASTM D 7361, using a 10kN Instron machine equipped with a fan oven. Heated aluminium plates with temperature control were used to apply the load, and strain was measured by means of LVDTs attached to the plates. As the specimens were under load, the temperature in the oven was elevated from 20ºC successively to 30, 40, 50 and 60ºC. These temperature steps have proved satisfactory for HDPE. Experience has shown that the creep of HDPE increases excessively above 60ºC and is not representative of long-term performance. Each temperature was maintained for a minimum of 3 hours (16 hours overnight) before the next temperature step. Tests were performed at 150, 175 and 250 kPa.

Tensile SIM tests were performed on a coated polyester geogrid, nominal tensile strength 80kN/m in the machine direction. Specimens consisted of single ribs. The tests were carried out following the procedure in ASTM D 6992, using a 5kN 5-to-1 lever creep machine loaded with dead weights and equipped with a fan oven. Roller grips were used to clamp the specimens, and strain was measured by means of LVDTs. With the specimens under load, the temperature in the oven was elevated from 20ºC successively to 34, 48, 62, 76 and 90ºC, thereby respecting the 14ºC steps recommended by Thornton (1998 a). Each temperature was maintained for a minimum of 3 hours (16 hours overnight) before the next temperature step. Tests were performed at 30, 40, 50 and 60% of the rib's average tensile strength.

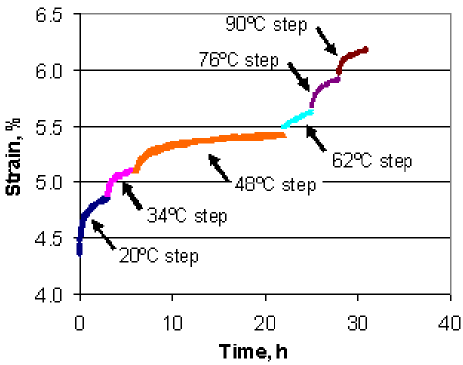

Figure 1. Strain vs Time curve from tensile SIM

An illustration of the "elongation vs time" curve obtained from tensile SIM test before shifting the data is given in Figure 1. The appearance of compressive SIM tests data is similar except that the strain, being negative, is inverted.

3 DATA ANALYSIS

3.1 *Curve shifting process*

The data obtained from SIM tests is analysed in order to obtain a smooth curve at the chosen reference temperature. The same procedure, consisting of three steps, is applied to each section of the strain curve corresponding to one period of constant temperature.

The first step consists of a vertical shift (see Figure 2). It is aimed at compensating for the thermal expansion effects that occur when the temperature is raised.

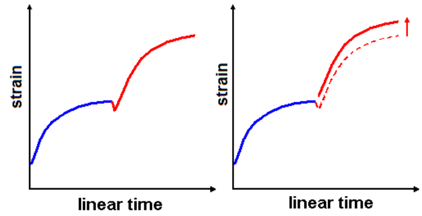

Figure 2: First step in applying SIM: vertical shift

The second step is a horizontal shift along the time axis (linear). This shift is made in order to compensate for the thermal and mechanical history of the specimen: its objective is to "replace" the curve on the time axis as if the test had been started at the temperature of the section that is being considered (see Figure 3).

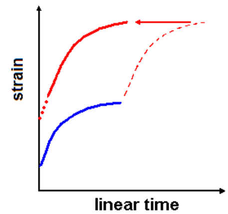

Figure 3: Second step in applying SIM: horizontal shift along linear time axis

When the second step has been completed for all strain sections, the shifted data should appear similar to what one would obtain from conventional TTS tests: a set of creep curves obtained for one single load at various temperatures. In practice this second step is achieved by iteratively varying the shift factor until a close match is obtained between the initial slope of the strain curve section and the end slope of the previous section in the plot of creep strain vs. log time.

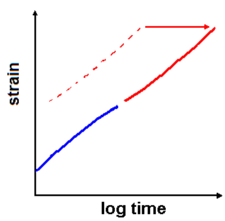

Figure 4: Third step in applying SIM: horizontal shift along log time axis

The third step then consists, as for conventional TTS tests, of a horizontal shift along the log-time axis in order to achieve a smooth master curve at the desired temperature (see Figure 4).

There are different methods to perform these shifts.

The simplest method consists of shifting the curves manually, through a number of iterations, until the curve observed seems as smooth as possible.

Alternatively computing methods may be used to model each section of the curve and determine the shift factors that lead to a continuous curve with a minimum difference between slopes. This method requires a good understanding of the tools and the mathematical functions used by the software.

3.2 *Measurement uncertainty vs. Curve shifting uncertainty*

The relative importance of the different contributions to the uncertainty is estimated here, based on the results of the SIM compressive tests.

3.2.1 *Measurement uncertainty*

For the equipment and test procedure that were used, the uncertainty linked to strain measurement is composed of the following contributions:

- Thickness was measured on each specimen to an accuracy of ±0.005 mm (normal uncertainty, equivalent to 1× standard deviation) over a typical sample's thickness of 5 mm, giving a normal uncertainty of ±0.1% strain. This applies equally to all measurements.
- Width was measured in both directions within 0.016mm over 100mm, giving two equivalent contributions of ±0.016% strain (normal uncertainty)
- The accuracy of the extensometry was ±0.005 mm (expanded uncertainty, representing 95% confidence limits and equivalent to 2× standard deviation) over 5 mm, giving an expanded uncertainty of ±0.1% strain.
- The accuracy of the applied load was ±0.32% (expanded). Considering load and strain uncertainties to be equivalent, for a 10% strain level the expanded uncertainty is 0.032% strain.
- Variability may occur due to an error in reading the reference temperature which is controlled to within ± 1ºC. Considering typical shift factors and strain increase per decade of time, the error associated is taken as 0.069% strain (rectangular).

Statistical combination of all these contributions gives an uncertainty due to measurement of 0.27%. The procedure is as defined in UKAS M3003 (2007).

3.2.2 *Manual curve shifting uncertainty*

In order to estimate the uncertainty related to curve shifting, the raw data obtained from three compressive SIM tests was given to three different operators for them to perform the curve shifting, using the simple "hand" method. The criterion to measure uncertainty was taken as the predicted strain value obtained following curves shifting for t = 10^5 hours. The different values obtained for each test and each operator are shown in Table 1. The averages and the standard deviation about these averages were calculated for each load.

This standard deviation gives an estimation of strain uncertainty linked to curve shifting of ±0.39%.

Table 1: Variable results obtained from curve shifting of compressive SIM data

	Strain at t = 10^5 h		
	Test 1 150 kPa	Test 2 175 kPa	Test 3 200kPa
Operator 1	10.26%	16.46%	11.91%
Operator 2	10.48%	15.05%	11.90%
Operator 3	9.96%	15.13%	11.81%
Average	10.23%	15.55%	11.87%

The uncertainties relating to measurement and to curve shifting can be combined to give an overall uncertainty by converting each single contribution into normal uncertainty (for expanded uncertainty, this is obtained by dividing the value by 2, and for rectangular uncertainty by √3), and taking the square root of the sum of the squares of all converted values. The overall uncertainty obtained is ±0.41% (normal). The expanded uncertainty for 95% confidence limit is ±0.82% strain. This can be particularly significant when considering strain levels relating to lower loads.

A similar calculation for tensile SIM gives an overall expanded uncertainty of ±0.25% strain. The variability in the strains predicted by different operators was less in this case (see Table 2), but the potential apparatus errors are greater, the largest being the control and measurement of temperature.

3.3 *Computer curve shifting methods*

It is also possible to derive a predicted creep curve mathematically by optimization techniques, i.e. by minimizing the square differences between the theoretical and measured strain curve segments while varying the shift factors and the creep curve parameters.

Table 2: Variable results obtained from curve shifting of tensile SIM data

	Strain at t = 10^6 h			
	Test 1 30% Load	Test 2 40% Load	Test 3 50% Load	Test 4 60% Load
Operator 1	5.81%	7.26%	8.55%	9.12%
Operator 2	6.04%	7.39%	8.55%	9.25%
Operator 3	5.85%	7.29%	8.57%	9.20%
Average	5.90%	7.31%	8.56%	9.19%
Computer	(*)6.60%	7.4%	(*)8.99%	9.35%

* after shifting, the curve did not reach 10^6 h. Extrapolation of the shifted curve to 10^6 h gave the strain value indicated

A simple analysis assuming a linear dependence of strain on log (time) was performed on data obtained from tensile SIM tests at 30, 40, 50 and 60% of the tensile strength of a geogrid. Table 2 gives the predicted strains for t = 10^6 hours and Figure 5 shows the computer predicted curve compared with those predicted by the three operators for a load of 30%.

The computer predicted curve on Figure 5 represents the optimized strain curve that is closest to a theoretical straight line.

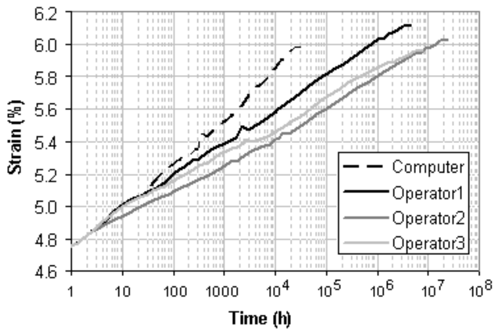

Figure 5: Shifted curves from tensile SIM test at 30% tensile strength

4 DISCUSSION

The results show that the expanded uncertainty (95% uncertainty, which is approximately twice the standard deviation) of SIM methods amounts to ± 0.8% strain in compression and ± 0.3% strain in tension. Variability in the very subjective process of manual shifting is responsible for about half in the case of compressive SIM. For tensile SIM the contribution of the curve shifting to the overall uncertainty is much smaller.

Note that the calculation of uncertainty is independent of the magnitude of the temperature steps . Errors in the control and measurement of temperature are estimated through their effect on strain. In our equipment the temperature was maintained to within ±1ºC, and generally even more closely, from a point at most two minutes after the temperature step was initiated.

It would only be possible to comment further on the success of computer predictions by attempting further algorithms on a wider set of results. A proposal for an alternative method of including the correction for thermal history and subsequent calculation was made by Yeo and Hsuan (2008).

The uncertainty values given do not include repeatability: the variation when the same test is preformed on specimens taken from the same sample by the same laboratory, which includes the variability of the material itself. For instance it is known that, for tensile SIM tests on Polyester based geogrids, there can be considerable variation in loading strain. This issue is addressed in practice by performing ramp and hold tests.

Reproducibility (the variation when the same test is performed by different laboratories) is not addressed here either. The need for carefully planned and controlled interlaboratory trials is emphasized if these popular and useful methods are to obtain worldwide credibility.

5 CONCLUSIONS

The results presented in this paper show that the uncertainty related to strain evaluation during SIM tests, which include measurement and curve shifting variability, is ± 0.8% strain in compression and ± 0.3% strain in tension (based on 95% confidence limits). This can be quite significant in relation to the strain values that are measured and needs to be kept in mind when using the results, particularly for design purposes.

The need for interlaboratory trials is emphasized.

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