Stepped Isothermal Methods Using Time-Temperature Superposition Principles for Lifetime Prediction of Polyester Geogrids

Hyun-Jin Koo, You-Kyum Kim and Dong-Whan Kim
Reliability Assessment Center, FITI Testing & Research Institute
892-64 Jegi2-dong, Dongdaemun-gu, 130-864, Seoul, Korea

Abstract.

The failure of geogrids used for soil reinforcement application can be defined as an excessive creep strain which causes the collapse of slopes and embankments. Accordingly, the lifetime is evaluated as a time to reach the excessive creep strain using two accelerated creep testing methods; time-temperature superposition(TTS) and stepped isothermal methods(SIM). TTS is a well-accepted acceleration method to evaluate creep behavior of polymeric materials, while SIM was developed in the last ten years mainly to shorten testing time and minimize the uncertainty associated with inherent variability of multi-specimen tests. The SIM test is usually performed using single rib of geogrids for temperature steps of 14°C and a dwell time of 10,000 seconds. However, for multi-ribs of geogrids, the applicability of the SIM has not been well established. In this study, the creep behaviors are evaluated using multi-ribs of polyester geogrids using SIM and TTS creep procedures and the newly designed test equipment. Then the lifetime of geogrids are predicted by analyzing the failure times to reach the excessive creep strains through reliability analysis.

1. Introduction.

Creep properties are important parameters in the design of goesynthetic-reinforced soil structures. Traditional approaches for the determination of creep behavior comprise the application to a sustained load and the measurement of the strain of geosynthetics as a function of time with elevated temperature steps. The conventional creep test uses multi-specimens/multi-temperature steps with test duration longer than 1,000 hrs[1] or 10,000 hrs[2]. For this reason, conventional creep tests are time consuming, expensive and contain uncertainty associated with inherent variability among specimens. To overcome this difficulties, it has been suggested to run stepped isothermal method(SIM)[3~5] which uses a single specimen per test and employs multi-temperture steps through the test duration. While the creep data is shifted using time-temperature superposition(TTS) principles, the single specimen/multi-temperature steps approaches allows the reduction of uncertainty associated with inherent variability of multi-specimen tests and tremendously short testing time(16~32 hrs).

The objective of this study is to introduce the SIM to the lifetime prediction of polyester geogrids. The results of creep master curves are analysed to validate the comparability of SIM and conventional TTS using statistical reliability analysis technique.

2. Experiments.

Accelerated creep tests(ACT) were performed on knitted polyester geogrids using the accelerated creep test equipment[6]. The load level of 50% ultimate tensile strengths(UTS) were applied to 100 kN/m knitted geogrids. In order to apply the conventional TTS, the creep tests(ACT-1) were performed on three specimens of multi-ribs of geogrids at three different levels of temperatures (75, 80 and 85°C) for a duration of 1,000 hrs. The SIM testing(ACT-2) was conducted using five specimens of single ribs of geogrids. Each specimen was allowed to reach equilibrium at 27°C prior to test initiation. Temperature was stepped 14°C every 10,000 seconds starting 27°C and ending at 90°C. Creep strains for the geogrids are plotted versus log time at each level of temperatures as shown in Fig. 1.

3. Results and Discussion

3.1. Time-Temperature Superposition

The creep strain curves obtained from ACT-1 were shifted on the log-time scale to obtain the master curves using the WLF equation 3[7] which provides a relationship between the test temperature, T(above T_g, the glass transition temperature), the reference temperature, T_R(usually ambient temperature), and the log of shift factors, a_T, as follows:

$$Log_{a_T}(T, T_g) = \frac{-C_1(T-T_g)}{C_2+T-T_g}, \qquad (1)$$

$$Log_{a_T}(T_g, T_R) = \frac{-C_1(T_g-T_R)}{C_2+T_g-T_R}, \qquad (2)$$

$$Log_{a_T}(T_R, T_g) = Log_{a_T}(T, T_g) + Log_{a_T}(T_g, T_R), \qquad (3)$$

where, C_1 and C_2 vary with material and reference temperature.

The creep strain curves obtained from ACT-2 were prepared for joining to make up the master curve by adjusting the starting times for each of the elevated stepped isothermal exposures. The first segment, which is done at the reference temperature, needs no adjustment. Subsequent segments do, to account for the effect of the creep history created by the prior exposures. This is accomplished by subtracting rescaling times, t′ from the test times for each elevated temperature step as shown Fig. 2. The rescaling process, when completed properly, will match the initial slope of each elevated temperature segment to the ending slope of the prior segment. Then, when connected end to end after small vertical shifts to account for thermal expansion, the creep-strain segments become a master creep curve as shown in Fig. 3. The master curves obtained from the conventional TTS and SIM shifting are shown in Fig. 4. Most significant is that the test time to generate one master curve is 16 hours for SIM shifting and 3,000 hours for the conventional TTS shifting.

3.2. Lifetime prediction

The regression analyses were run using log time as a predictor variable and the log strain as a response variable in order to estimate the failure times for the master curves obtained from the conventional TTS and SIM shifting. The failure times and long-term creep strains were extrapolated using the regression equations. And then, we predicted the B_{10} lifetimes of geogrids by applying Weibull distribution and estimating the reliability statistics[6].

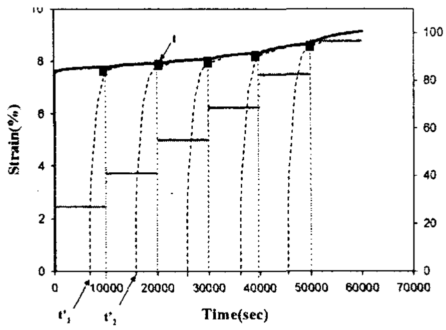


Figure 1. Stepped Isothermal methods with rescaling

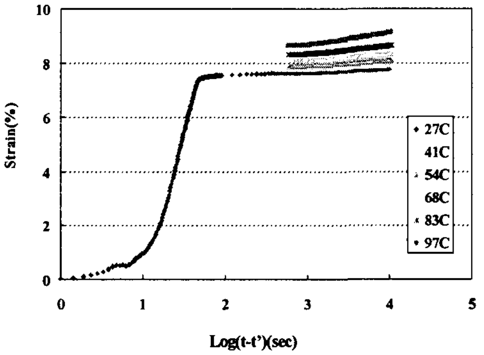


Figure 2. Creep strain vs. log(time) after rescaling

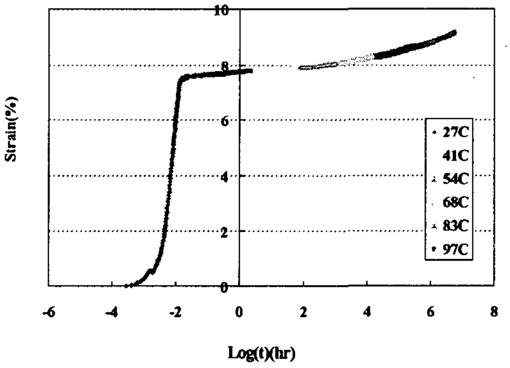


Figure 3. SIM shifting at the step one reference temperature

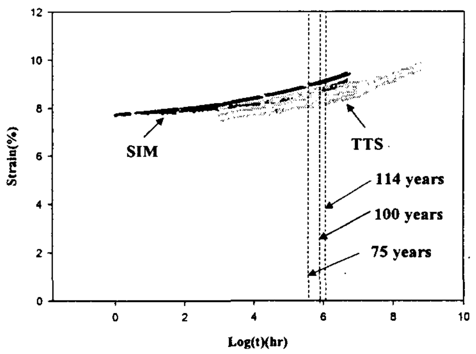


Figure 4. SIM vs. conventional TTS master curves

3.3. Comparison of SIM and conventional TTS for determining the lifetime of geogrids

The results obtained from two shifting methods are compared using statistical data analysis technique. For the geosynthetics community, long term generally means 75, 100 years or sometimes 1,000,000 hours, which is 114 years. Therefore, the creep strains were estimated at 75, 100 and 114 years and then analysed using T-test given in Table 1. The analysis results have shown that there is no evidence that the creep strains obtained from both methods are different at 75, 100 and 114 years with 95% statistical confidence. It means that the log-term creep strains obtained from SIM shifting agree well with those obtained from the conventional TTS.

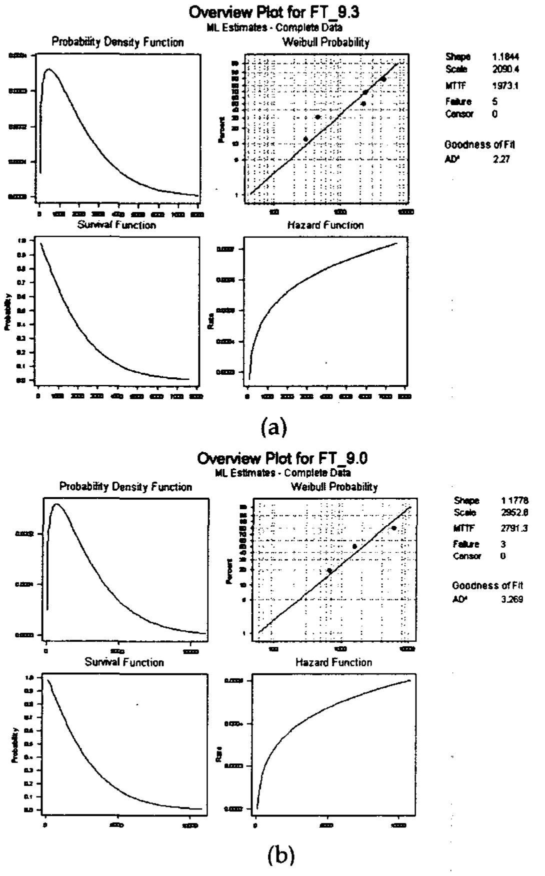
In order to compare the lifetimes obtained from two shifting methods, the reliability analyses were run and the results are shown in Fig. 5. The estimated creep strains are 9.3% for the SIM shifting while 9.0% for the conventional TTS shifting at 100 years of B_{10} lifetime at 27°C with 90% statistical confidence. The reliability analysis results for both testing method agree well with each other for the shape of probability density function, reliability function and failure rate which is the determinant of the failure mechanism. This implies that the

SIM shows high feasibility as a substitute for the time consuming and expensive conventional TTS.

In addition, the SIM shows good agreement with conventional TTS even though the conventional TTS used the multi-ribs of geogrids while the SIM used single-ribs of geogrids specimens. This means that single-ribs of specimens might be used for the SIM tests if the capacity of creep test equipment is not enough to handle the multi-ribs of specimens.

Table 1. Comparison of SIM & TTS Methods-Basic Statistical Analysis

Failure time(Yrs.)		N	Creep Strain(%)	95% C.I. for Creep Strain	T-value	*p*-value
75*	SIM	5	8.744	(8.482, 9.007)	1.76	0.129
	TTS	3	8.470	(7.691, 9.249)		
100*	SIM	5	8.785	(8.519, 9.051)	1.75	0.131
	TTS	3	8.513	(7.752, 9.274)		
114*	SIM	5	8.803	(8.534, 9.072)	1.75	0.213
	TTS	3	8.531	(7.776, 9.286)		



(a)

(b)

Figure 5. Reliability analysis results (a) for conventional TTS and (b) for SIM methods

4. Conclusions

We have validated the use of the stepped isothermal method(SIM) for lifetime prediction of a knitted geogrid. SIM results were compared to conventional results through statistical reliability analysis technique.

The estimated creep strains and predicted lifetimes for both methods agree well with each other. The results show that the estimated creep strains for SIM and conventional TTS reach 9.0 and 9.3% after 100 years of usage with 90% statistical confidence, respectively.

The SIM, which allows the reduction of test time by 99.5%, is recommended for predicting lifetimes of polyester geogrids without the uncertainty associated with the inherent variability among specimens.

Acknowledgement: We are grateful to Korean Ministry of Commerce, Industry and Energy for supporting this work.

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