Accelerated Creep Testing of Geogrids for Slopes and Embankments: Statistical Models and Data Analysis

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Abstract
The failure of geogrids can be defined as an excessive creep strain which causes the collapse of slopes and embankments. In this study, the accelerated creep tests were applied to two different types of polyester geogrids, at 75, 80, 85℃ by applying 50% load of ultimate tensile strengths using a newly designed test equipment which is allowed the creep testing at higher temperatures. And then the creep curves were shifted and superposed in the time axis by applying time-temperature supposition principles. In predicting the lifetimes of geogrids, the underlying distribution for failure times were determined based on identification of the failure mechanism. The results indicate that the conventional procedures with the newly designed test equipment are shown to be effective in prediction of the lifetimes of geogrids with shorter test times. In addition, the predicted lifetimes of geogrids having different structures at various creep strains give guidelines for users to select the proper geogrids in the fields.

1. INTRODUCTION

The fabric type geogrids are made with a high tenacity polyester filament using a conventional weaving and/or knitting process. Commonly, the fabric type geogrids are then coated with copolymer resins such as PVC (poly vinylchloride), bitumen, PP (polypropylene), acrylic resins, latex and other rubbery materials, which contain alight stabilizer and antioxidant[1, 2]. Since the geogrids possess high tensile properties in nature, they are frequently used as the reinforcement in slopes, embankments, segmental retaining walls and so on[3]. The required service lifetime of geogrids used for reinforcement of slopes and embankments varies according to the sensitivity of the environmental condition and required safety factor. Typical lifetimes for slopes and embankments are 50 ~ 100 years. This implies that the functional engineering properties of the geogrids should remain within acceptable limits during the required service life.

Usually, the lifetimes of geogrids are assessed as the long-term creep behavior which causes the shape deformation and collapse of the slopes and embankments. Therefore, various investigators[5, 6] evaluated the time-temperature creep relationship on various geotextiles through accelerated creep testing procedures. Bush[7] evaluated temperature shifts on geogrids at temperature from 10℃ to 40℃. Jeon et. al.[8] performed the accelerated creep tests on polyester geogrids with various loading levels and temperatures up to 50℃. These studies showed the applicability of predicting creep strains from elevated temperature creep tests. In this study, the long-term creep properties are examined above T_g (75℃~90℃) by conventional TTS (time-temperature superposition)[4] using a newly designed test equipment for the first time. The lifetimes of geogrids are predicted through reliability analyses[9]. It is hoped that via careful interpretation and extrapolation of short-term creep data, accurate long-term creep behavior can be predicted.

2. TIME-TEMPERATURE SUPERPOSITION PRINCIPLE

Deformations, such as creep strain, occur relatively rapidly when load first applied, but the rate of increase decreases with time. Consequently, graphs produced with log time as the abscissa are indispensable for describing viscoelastic behavior. The precise way that increasing temperature accelerates these physical processes, governs how creep response can be shifted along a log time scale. The relationship between time and temperature superposition can be explained with the shift factor at the accelerated temperatures. When creep strain is plotted versus time for different temperatures, the creep strain curves along the log of time axis can be shifted until the curves overlap and a single curve is obtained. This curve, the master curve, represents strain for longer time intervals at the reference temperature. The shift factor can be obtained using the WLF equation suggested by William, Landal and Ferry[4].

$$E(T_{0,}\ t) = E\left(T, \frac{t}{a_T}\right) \quad (1)$$

$$log a_T = \frac{-C_1(T - T_0)}{(C_2 + T - T_0)} \quad (2)$$

In the WLF equation, C_1 and C_2 vary with material and reference temperature. If the glass transition temperature(T_g) is used for extrapolation, C_1 and C_2 take the values 17.4 and 51.6[4], respectively.

3. EXPERIMENTAL

3.1 *Accelerated Creep Test Equipments*

The variations in types of polymers and properties of geosynthetics resulted in the development of different creep testing equipment to accommodate the various requirements for clamping mechanisms, specimen's dimensions, temperature ranges, loading levels, testing time, and methods of creep measurement. The accelerated creep test equipment was designed with the following considerations. Fig. 1 shows the newly designed creep test equipment.

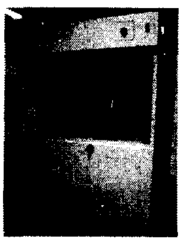


Figure 1. Accelerated creep test equipment.

The height of loading frame was designed to test upto a 50cm long geosynthetic specimen. The specimen length was 300mm long and width was 200mm wide as in ASTM D4595[11] "Test method for Tensile Properties of Geotextiles by the Wide Strip Method" .

A servo motor system that applied the extension loads on the bottom clamps was used in the testing equipment. Such a system offered the flexibility of applying higher loads to each loading frame independently. However, the equipment was costly and required precision and maintenance to keep the applied loads constant within an acceptable range of accuracy during the testing period. The design of the loading system permitted using different clamps according to the types of geosynthetics tested in order to prevent slippage or breakage of the specimens inside the clamps. Grip type claps, according to ASTM 4595, were used in testing the geogrids in the creep testing program as shown in Fig. 2.

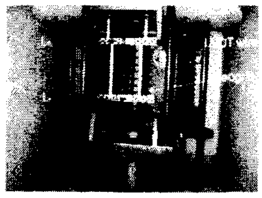


Figure 2. Loading system and clamping mechanism.

Creep tests at elevated temperatures were carried out for two types of geogrids inside temperature-controlled ovens. The ovens were constructed so that 3 sets of loading frames are located inside the ovens which permit the 3 specimens of geogrids tested simultaneously as shown in Fig. 2. The applied load at each frame was monitored using a load cell mounted above the upper clamp. Displacement was monitored by an LVDT(linear variable differential transformer) mounted on the upper plate of the loading frame. The instrument was connected to a data acquisition system and a computer for response monitoring and recording at specific time intervals.

3.2 *Accelerated Creep Test*

Creep tests were performed on two different types of geogrids shown in Fig. 3 according to RS K 0009[10] under 50% of UTS(ultimate tensile strengths) using a newly designed accelerated creep test equipment. Table 1 shows the physical properties of geogrids.

These tests were performed on three specimens of geogrids for each type at three different levels of temperatures (75, 80 and 85℃) for duration of 1000 h. The temperature of the oven was maintained by hot air blower within ±1℃ of accuracy.

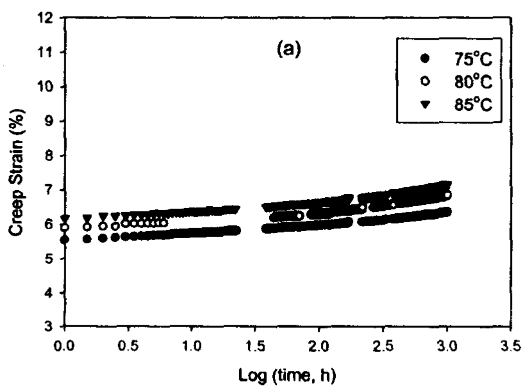
Table 1. Physical properties of polyester geogrids

	woven		knit	
	MD	CD	MD	CD
tensile strength (kN/m)	68.2	32.1	124.3	35.6
elongation (%)	9.7	12.7	11.1	13.8

4. RESULTS AND DISCUSSION

Creep strains for woven type of geogrids are plotted versus log time at each loading level and temperature as shown in Fig. 3, respectively. The results show that the creep strain at 50% loading level shows a "typical"plot of strain(or its log) versus log time for both types of geogrids. Initially, the rate of strain increase is high a wear in period. After a short time, the rate of strain increase becomes relatively constant and remains constant for a considerable time, corresponding to the straight portion of the plot. Finally, the rate of strain increase may increase again a wear-out period.

For woven type geogrids, the creep strain reaches 7.14~7.44 at 85℃ after 1000h while the creep strain reaches 9.63~9.87% for knit type geogrids. The knit type geogrids show much higher creep strain than woven type geogrids. This is due to the structural differences explained in the following section.



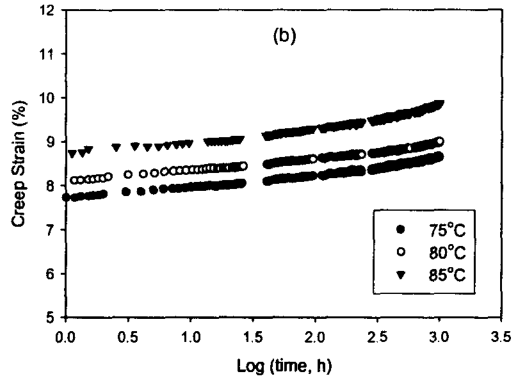


Figure 3. Creep Strain curves of (a) Woven Type, Specimen #1 and (b) Knit Type, Specimen #1.

4.1 *Time-Temperature Superposition*

The creep strain curves under 50% loading level were shifted on the log-time scale to obtain the master curves using the shift factors which were calculated based on T_g as a reference temperature using the Equation 2 as shown in Table 2. The shifting process is illustrated in Fig. 4. The regression analyses were run using the log time as a predictor variable and the log strain as a response variable in order to obtain the regression equations for extrapolation.

Table 2. Shift factors using WLF equation

Temperature(℃)	Shift factors
75	1
80	-1.54
85	-2.84

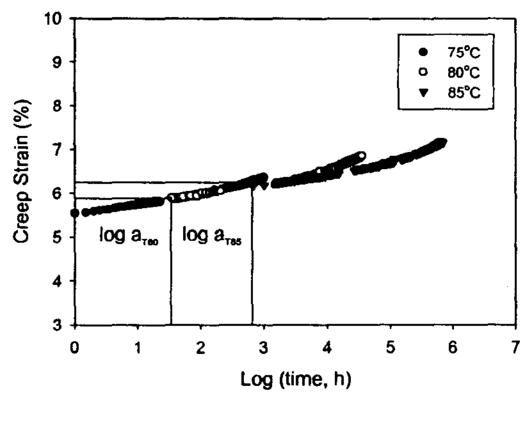


Figure 4. Time-temperature superposition of creep strain curves under 50% UTS Woven type specimen #1.

The three master curves were obtained for each type of geogrids with the results of linear regression analyses. Even though only one master curve for each type is shown in Fig. 5, the three replicated master curves show similar shapes while the creep strains after TTS are various.

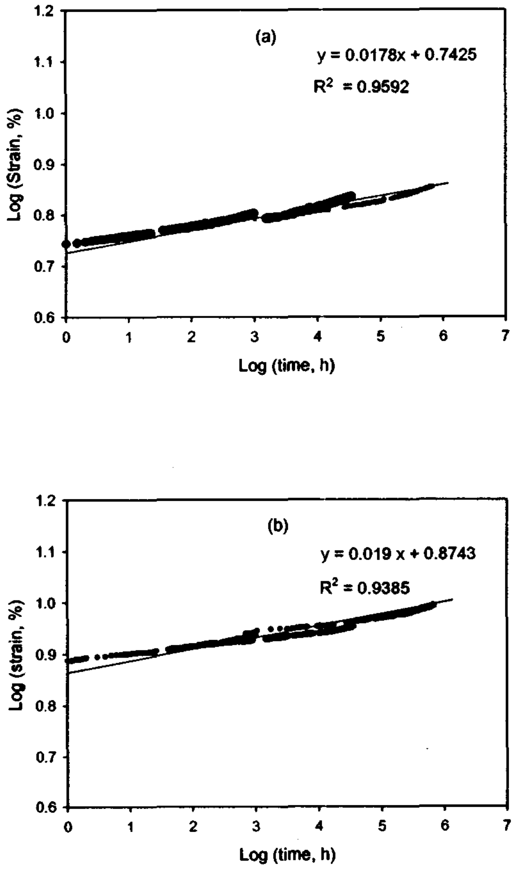


Figure 5. Master curves of (a) Woven type specimen #1 (b) Knit type specimen #1 under 50% UTS.

The estimated failure times were extrapolated at 7.3%~7.7% creep strain for the woven type geogrid and 9.6%~10% creep strain for the knit type geogrid using the linear regression equations. The failure times for both type of geogrids are estimated at various creep strains as shown in Table 3. The estimated failure times are accurate enough for practical usage since R^2 values of regression equations are between 0.93~0.97. The lifetimes will be predicted and compared in the following section.

Table 3. Estimated failure times at various creep strains for woven and knit type geogrids

failure times of woven type geogrids(yrs)			
creep strain at failure (%)	specimen #1	specimen #2	specimen #3
7.3	700	191	98
7.4	1504	426	216
7.5	3197	939	467
7.6	6728	2047	1001
7.7	14023	4417	2123
failure times of knit type geogrids(yrs)			
creep strain at failure (%)	specimen #1	specimen #2	specimen #3
9.6	54	57	152
9.7	94	115	249
9.8	162	228	405
9.9	277	449	656
10.0	471	879	1057

4.2 *Lifetime Prediction*

We predicted the lifetimes of geogrids through estimating failure distributions by applying four different statistical distributions to failure times using MINITAB statistical software and test the goodness-of-fit using Anderson-Darling statistics(AD*).

From the stand point of reliability considerations, 10 percentile of the lifetime distribution with 90% statistical confidence are often of concern. Therefore, we predicted the B_{10} lifetimes of geogrids to reach various creep strains. The results show that Weibull distribution fit to failure times for both types of geogrids the best based on Anderson-Darling statistics. This results show that the hazard rate of both cases follow an IFR since the shape parameters for the woven type geogrids are slightly greater than 1 and those for the knit type geogrids are 2~4. However, the failure mechanism of two types of geogrids might be different due to different shape parameters.

The B_{10} lifetimes are plotted versus creep strains with regression models shown in Fig. 6. The B_{10} lifetimes of the woven type goegrids are between 10~400 years in the range of creep strains of 7.3~7.7% while those of the knit type goegrids 15~300 years in the range of creep strains of 9.6~10%. In order to compare the lifetimes of different types of geogrids, the creep strains were estimated at B_{10} lifetime of 100 years using the regression equations shown in Fig. 6. The result implies that the creep strain of woven type geogrid is 7.52% while the creep strain of knit type geogrid is 9.85% after 100 years of usage. This is due to the structural differences.

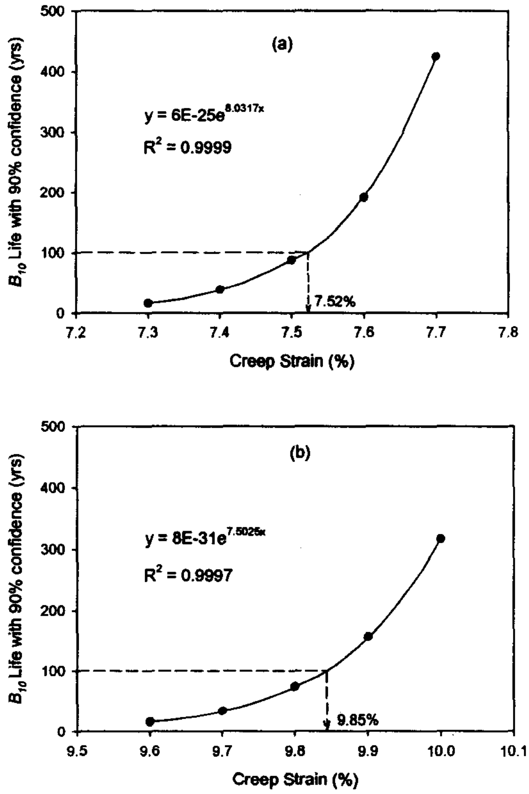


Figure 6. Life time prediction at various creep strains of failure (a) Woven type geogrids, (b)Knit type geogrids under 50% UTS at 100 year.

The warps and wefts are crossed each other to form the woven structure under high tension in the woven type geogrids while the cross sections between warps and wefts are bonded through the knitting process in the knit type geogrids. The results of reliability analyses are given for both type of geogrids at B_{10} lifetime of 100 years in Fig. 7 and 8.

The woven type geogrids might be used under more severe environments than the knit type geogrids. However, the knit type of geogrids are more economical than the woven type of geogrids since the manufacturing processes of knit type geogrids are 3~4 times faster than those of woven type geogrids. Considering the engineering safety and economical aspects, the results might give the guidelines for users to select proper geogrids.

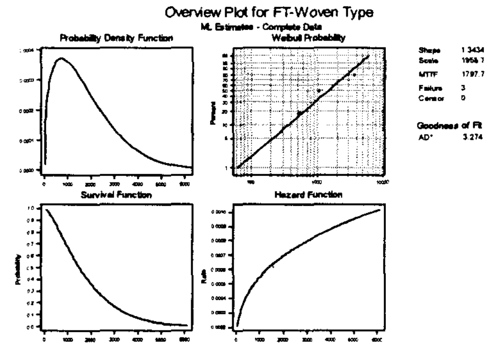


Figure 7. Results of reliability analyses for Woven type geogrids.

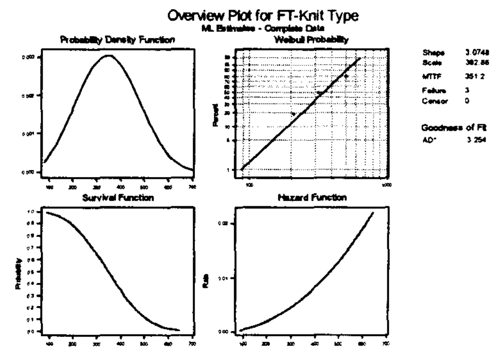


Figure 8. Results of reliability analyses-Knit type geogrids.

4.3 *Reduction Factor of Safety*

The reduction factor of safety(*RF*) could be calculated from the predicted creep values. The calculated method for that was suggested by R. Koerner[2] and is presented as follows,

$$RF = \frac{T_{AS}}{T_{DS}}, \qquad (6)$$

where T_{AS} is allowable strength(sustained ASTM D5262[12] testing in which the curve becomes asymptotic to a constant strain line, of 10% or less), and T_{DS} is the design strength of the geogrids. The 50% loading of UTS means 62 kN/m load applied to the knit type geogrids, which is 62%(62kN/100kN) of the design strength when the creep strain is asymptotic to 10%. The allowable strength will reflect this type of information in that the partial factor of safety against creep will be the inverse of 62%, which is 1.60. In the same way, the factor of safety for woven type geogrids will be 1.75 with 7.5% of creep strain. This implies that the factor of safety for the woven type might become less than 1.75, economically.

5. CONCLUSIONS

(1) We have designed new accelerated creep test equipment and a procedure for predicting lifetimes of polyester geogrids by applying statistical failure distributions and time-temperature superposition principles.

(2) The procedure was evaluated for two different types of polyester geogrids of an operating temperature above its glass transition temperature(75℃) using the newly designed equipment for the first time. Using this procedure and equipment, the lifetime of geogrids can be predicted longer than 100 years.

(3) The estimated creep strains for woven and knit types of geogrids are 7.52 and 9.85% after 100 years of usage, respectively.

(4) We also found that the lifetimes of polyester geogrids follow the Weibull distribution and both types of geogrids satisfy the required service life used as the reinforcement in slopes and embankments.

(5) The results of lifetime prediction at various creep strains give the guidelines for users to select proper geogrids according to the sensitivity of environmental condition and required factor of safety.

(6) The newly designed procedure and equipment could be applied to predict lifetimes of other geosynthetics.

ACKNOWLEDGEMENT

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

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