ACCELERATED CREEP TESTING AND QUALITY ASSURANCE

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Abstract: During the 1980's the use of accelerated creep testing at temperatures up to 400C with Time-Temperature-Superposition (TTS) was established as the safe means of predicting the Long-Term Design Strength (LTDS) of geosynthetic reinforcement materials. To minimise extrapolation, testing was continued to 10,000 hours or more. Then in the 1990's increased temperatures were introduced but the principle of 10,000hours of testing was retained. Under this regime regular Quality Assurance testing is not feasible. Previous efforts to shorten testing times have concentrated on the Stepped Isothermal Method, which has now successfully demonstrated the use of high temperatures and short testing times for some products.

It has now been found that accelerated conventional creep testing at higher temperatures can enable the safe prediction of the LTDS with individual tests limited to around 1000 hours duration. A specially designed accelerated test series utilizing data generated in 100 hours or less has been created for subsequent comparison with the product family master curves for regular ongoing Quality Assurance, e.g. at the annual renewal of CE Mark certification.

It is now possible to safely introduce products to market more quickly and to give the market more testing choices for implementing the ongoing quality assurance that is rightly being demanded.

1 INTRODUCTION:

During the 1980's the use of accelerated creep testing at temperatures up to 40^{0}C with Time-Temperature-Superposition (TTS) was established as a safe means of predicting the LTDS geosynthetic reinforcement materials. To minimise extrapolation, testing was continued to 10,000 hours or more (McGOWN et al (1985), YEO (1985), WRIGLEY (1987)). Then in the 1990's increased temperatures were introduced but the principle of 10,000hours of testing was retained. (WRIGLEY et al (1999))

In recent years, efforts to shorten this testing period have concentrated on the successful development of the Stepped Isothermal Method of creep testing (SIM). Using SIM, the long term performance of some PP and PET geosynthetics can now be predicted with test durations of less than 1000 hours. (Thornton & Baker (2002), Thornton et al (1998))

During the autumn of 2002 a new range of 4 punched-drawn HDPE Geogrids was developed and manufactured by The Qingdao Etsong Geogrids Co., Ltd.. Immediately these products were subjected to a series of creep tests in the company's laboratories, with the objective of making a safe determination as quickly as possible of their Long Term Design Strengths for design lives of $10^{6.022}$ hours (120 years). (the LTDS)

In view of the success of SIM with other products a test programme was developed for the new products to investigate whether conventional creep tests could also be used to determine their LTDS with maximum test durations of around 1000 hours.

2 BASIS OF TEST PROGRAMME:

Initially, the plan was to take all samples to rupture. However, this proved to not be feasible. One sample ruptured at 17.94% strain and a few samples ruptured at strains between 20% and 40%. The remaining tests were terminated close to, or above 20% strain either because the sample slipped in the clamp jaws of the test rig or, particularly with the later tests, because the strain was significantly in excess of 20%.

By the time these later tests were terminated the performance of the products was more clearly understood and it had been decided that for this testing the "Failure" for a sample would be defined as the time to 20% strain, or the time to rupture, whichever was the shorter. The performance of any reinforcement product at strains greater than this is of no significant interest to a geotechnical engineer.

This definition forms the basis of this test programme and the LTDS derived for each product.

Fig. 1: Creep tests in progress at 20^{0}C

In order to provide sufficient data for TTS at least three data points were needed at each temperature with durations spread from around 1 hour to around 1000 hours. For 4 products and 3 temperatures this meant a minimum of 36 tests. In the event a total of 65 tests were completed in accordance with the methodology of ISO13431, though not the specified load levels of that standard. Of the 65 tests, 3 had durations of 1000-2000 hours, 2 had durations of 2000-5000 hours and 60 had durations of less than 1000 hours

3 TESTING:

The tests were carried out in 3 separate temperature-controlled laboratories at temperatures of 20^{0}C, 40^{0}C and 50^{0}C. 5 of the test stations used are shown in Fig.1.

These test stations are designed for ease of use and low cost. The creep load is a dead weight hanging directly on the sample. The gauge-length of each sample is the centre 3 pitches of the grid. This gives initial gauge lengths of around 750mm. With such long gauge lengths measurement with a tape measure to the nearest 0.5mm gives an accuracy of ±0.25mm, or approximately ±0.33%.

The temperature of each test room was controlled to ±1degC

4 TEST RESULTS:

Typical results of the tests, plotted as Strain vs. Log(Time), are illustrated in Fig 2.

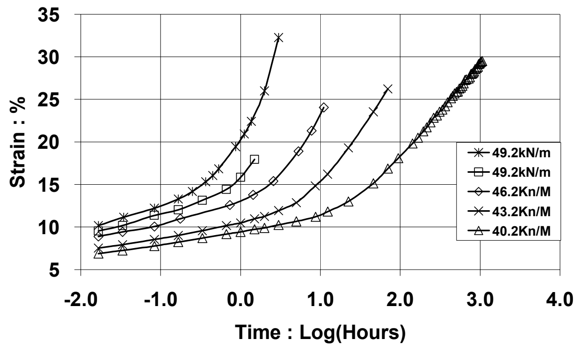


Fig 2: Creep Curves for Product A at 20^{0}C

From this data, the time to reach failure (as defined above) was determined for each test.

5 DETERMINATION OF LTDS

5.1 *The analysis process from Creep Data to LTDS consists of 3 stages:*

5.1.1 *Find Time-Shift Factors for each product:*

In this stage each product is treated separately. Block-shift factors are applied to the individual test times at 40^{0}C and 50^{0}C to obtain equivalent 20^{0}C times for these tests.

The optimum shift factors are determined by obtaining a straight-line plot of log(test load) vs. log(test time) with a minimum deviation of the test points from the line of this plot.

5.1.2 *Find and apply mean shift factors*

The optimum shift factors may not be exactly the same for each product. This is one of the manifestations of differences between different batches of product. This difference can be negated by averaging the individual shift factors and plotting the creep data using the mean shift factors.

5.1.3 *Normalisation and determination of 95% Confidence Limits:*

In previous work (Wrigley et al (1999)), data sets from different products within a range have been normalised on the basis of the intercepts of their individual trend lines with 10^6 hours. This is towards one extreme of each data set. For this programme, it was decided that it would be more appropriate to use a point in the centre of the data sets, i.e. at 10^3 hours.

Finally, a plot giving the lower 95% lower confidence limit for the data is drawn. From this a relationship between the normalised loads at 10^3 hours and the mean and lower confidence limits for the LTDS at 10$^{6.022}$hours can be derived and the LTDS's calculated.

5.1.4 *Adjust the LTDS to take account of variations in Production:*

The LTDS's calculated directly from the data are of the individual batches tested. These must then be corrected to allow for the variations that will occur in production. To do this it is necessary to find the production factor most closely related to the batch LTDS's, then make adjustment to allow for the minimum value that this factor could have.

5.2 *These stages were applied to the data of this study as follows:*

5.2.1 *Determination of Time-Shift factors for Each Product:*

First, the data for a product are plotted as Log(load) vs. Log(Time to failure or 20%) as illustrated in Fig 3

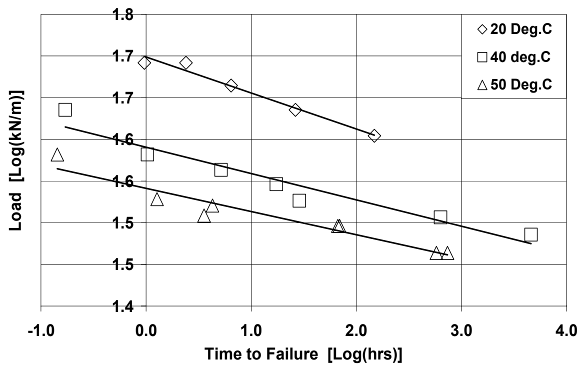


Fig 3: Load vs. actual test time

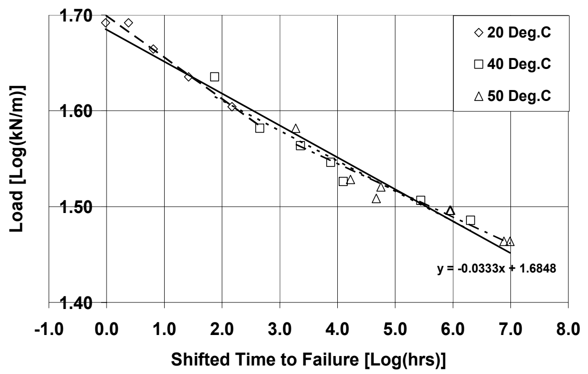


Fig 4: Load vs Time shifted by optimum factors

Then, the data for 40^{0}C and 50^{0}C are shifted to the right until a best-fit straight line through all points may be plotted, as illustrated in Fig 4.

In Fig 4 the best-fit straight line through the shifted points is shown. The positioning of the data points relative to this line suggests that a curved plot may be a closer fit to the data. This feature is discussed later in this paper.

5.2.2 *Determination and Application of Mean Shift Factors:*

from the analyses of Stage 1 the shift factors shown in the first 4 columns of figures in Table 1 were determined. In the fifth column of Table 1 is shown the mean of the individual shift factors. These means were then used to re-analyse and plot the creep data for each product as illustrated in Fig 5.

Table 1: Time Shift Factors

Temperature Step	Shift Factors				
	Product				Mean
	A	B	C	D	
20^{0}C-40^{0}C	440	750	600	548	584
40^{0}C-50^{0}C	30	40	35	34	34

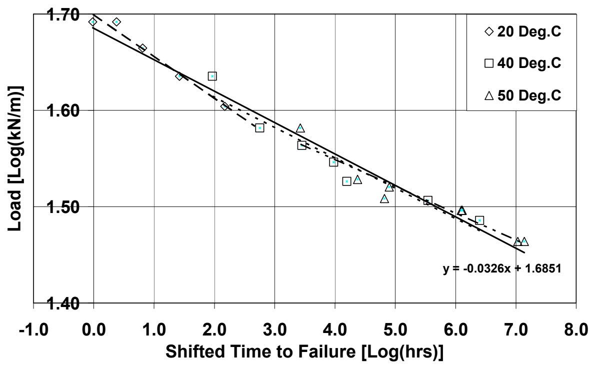


Fig 5: Load vs Time for Product A shifted by mean factors

The visual difference between Figs. 4 & 5 is very little. The maximum difference from the optimum to the mean shift factors for any product is less than 0.1 units on the Log(Time) axis.

5.2.3 *Normalisation and initial determination of LTDS's based on 95% Confidence Limits:*

From the mean shift analyses, the load each grid would carry to failure or 20% for 10^3 Hours is shown in Table 2:

Table 2: Individual Product Creep Strengths at 10^3 Hours

Product	Strength for 10^3 Hours (Kn/M)
A	38.708
B	49.522
C	72.144
D	89.310

These figures were used as the basis of the normalisation of the data for the different products.

Firstly, the data for all 4 products from the Mean Shift Analyses was plotted together as shown in Fig. 6.

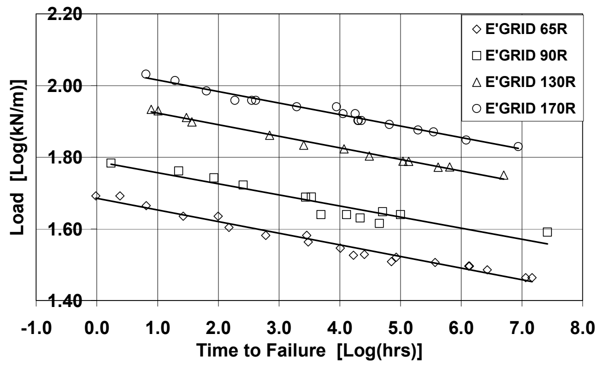


Fig 6: Load vs Time for all products shifted by mean Factors

Then the individual test loads were divided by the appropriate load at 10^3 hours and the data plotted as Log(Normalised Load) against Log(Time) to give Fig 7. As with the individual plots, the best fit straight line was then plotted through the data as shown in Fig. 7.

From students' t tables it was determined that the 95% confidence limit for 60 records is 2.00 Standard Deviations displaced from the mean. This is the basis of the 95% Confidence line plotted in Fig7.

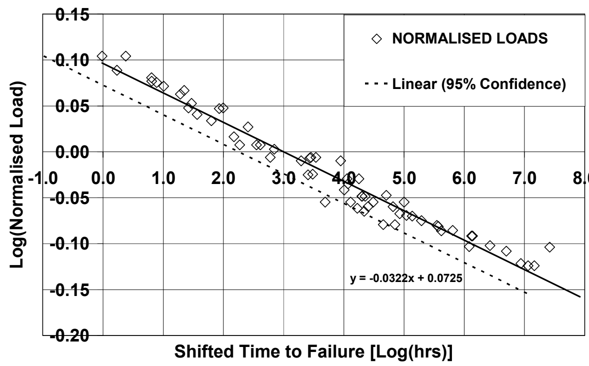


Fig 7: Normalised Data

From the equation for the Lower 95% Confidence Line, the LTDS at 120 years is given by:

$$LTDS_{120yr} = (\text{Mean Load})_{1000hrs} \times 0.756 \qquad (1)$$

It can be clearly seen that this gives a safe, even conservative, means of determining the LTDS of these product batches tested. A curved polynomial would obviously give a better fit to the data points than the straight line. However, as these products are new to the market it was decided that the adoption of the conservative straight-line plot would be prudent at this time.

5.2.4 *Determination of the LTDS of production materials:*

LTDS's calculated using Equation (1) are compared with two key production factors in Table 3. These factors are:

- Batch Tensile Strength (ISO 10319): T_{Batch}
- The thickness of the sheet used to make the batch: S_{Batch}

Table 3: LTDS and Production Factors

Product	LTDS (kN/m)	T_{Batch} (kN/m)	S_{Batch} (mm)	LTDS/T_{batch}	LTDS/S_{Batch}
A	29.26	73.74	3.15	0.397	9.29
B	37.44	100.4	4.16	0.373	9.00
C	54.54	148.0	6.04	0.369	9.03
D	67.51	185.6	7.50	0.364	9.00

It can be seen that the LTDS's are more closely related to thickness than short-term strength as measured by ISO 10319. This is not surprising as the failure mechanisms that dominate in a test of around 1 minute in duration can be expected to be different from those that come into play at much longer load durations.

It was therefore concluded that full allowance could be made for batch-to-batch variations in product by basing the final product LTDS's on:

A: The minimum value of LTDS/S_{Batch} from Table 3 of 9.00kN/m/mm

and

B: The minimum values of thickness for each product that could be expected in production.

From a study of product and production data appropriate values for minimum thicknesses were determined and values for the LTDS's of production materials calculated, as shown in Table 4.

Table 4: LTDS values for Production Materials

Product	Minimum Thickness (mm)	LTDS @ 10^6.022 hours (kN/m)
A	3.06	27.6
B	4.01	36.1
C	6.00	54.0
D	7.28	65.5

6 QUALITY ASSURANCE

6.1 *Model*

In order to carry out quality assurance of creep performance it is first necessary to generate master creep performance curves for the family of products under study. This can be done as follows

The 95% Confidence plot of Figure 7 follows the general formula:

$$\mathrm{Log(Load)} = a - b\mathrm{Log}(T) \qquad (2)$$

In which

a = 0.0725
b = 0.0322

Of these, the slope, "b", is a characteristic of this family of products and "a" is particular to the load being plotted. In this case: the normalised load.

To now generate master plots for each product in the family appropriate values for "a" can be calculated by inserting the fixed value of "b" into Equation (2), together with the values for LTDS's from Table 4. This gives the values for "a" shown in Table 5:

Table 5: Values of "a" for Product Family

Product	"a"
A	1.6348
B	1.7514
C	1.9236
D	2.0101

Using these constant values in Equation (2) a family of master creep performance plots for the products can be plotted as shown in Figure 8. As the loads used to generate these plots are lower bound values then so are these plots lower bound curves of performance.

For convenience of use in a quality assurance role Figure 8 is plotted as linear load against time.

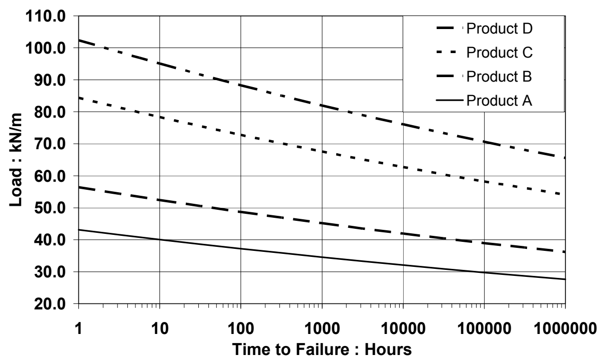
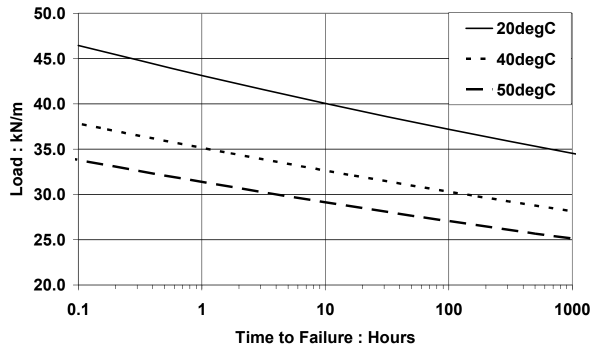


Figure 8: Lower-bound Master Creep Performance Plots

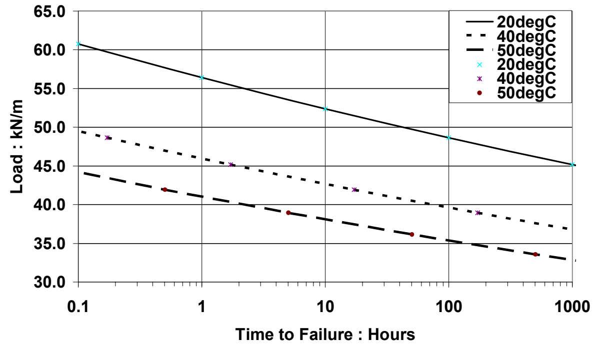
To further facilitate the use of these plots they can then be broken down into plots in real time for each temperature used in testing for each product. This is done by back-analysing the plots of Figure 8 with the time-shift factors of Table 1. These plots are shown in Figures 9 a, b, c, and d.

In order to confirm that the performance of a batch of product is consistent with these plots two aspects need to be studied: the time to failure of individual samples and the appropriate time-shift factors for the batch.

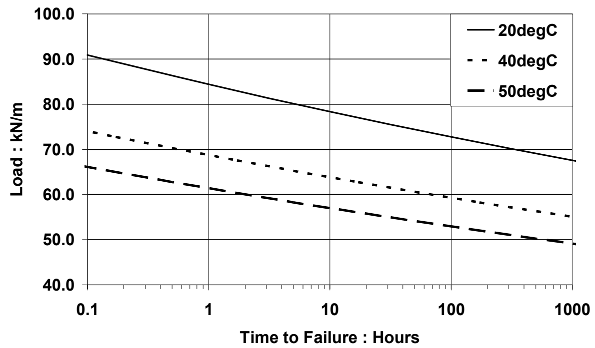
Both can be checked by comparing the trend lines of tests at 2 different temperatures with the master plots. The first is checked by comparing the position of the trend lines to those of the master plots. For the second, If both trend lines have slopes that are substantially the same as the slopes of the master plots then the shift factors are consistent.



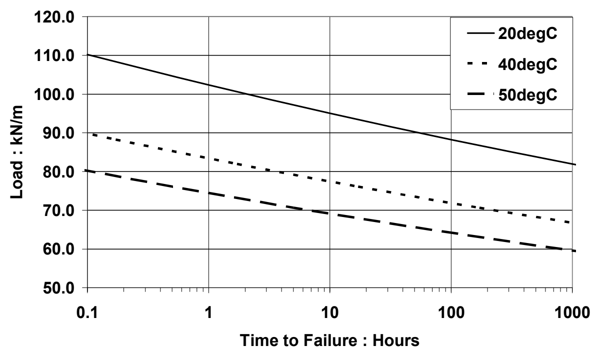
(a) Product A



(b) Product B



(c) Product C



(d) Product D

Fig 9: Lower-bound Master Creep Performance Plots for each Product in the Family.

6.2 *Proposed Test Programme for QA*

If it was only necessary to check the times to failure of individual samples, then a simple test programme of one or two sample loads at each of two temperatures would suffice. However, as it is necessary to plot trend lines at each temperature, then there must be at least 3 useable results at each temperature, spread over a significant time period. Therefore the simplest programme that could be used would be to load three samples at each of two temperatures that would be expected to have failure times of 1, 10 and 100 hours.

However, deciding what loads to use for just three tests at one temperature is not easy. As the master plots are lower-bound performance expectations, then most samples will perform significantly better than the plots predict. The additional time to failure for many could easily be one decade of time or more

It is therefore recommended that the following procedure be adopted:

A: Hang three samples at each of two temperatures using loads determined from the 1, 10 and 100 hour intercepts of the master plots.

B: After 24 hours study the performance of the samples at nominally 1 and 10 hour loads. If their times to failure are more than twice the nominal values then hang two more samples (if necessary) at revised loads predicted to give failure in 1 hour and 100 hours. (We say “if necessary” as the sample with a nominal failure time of 10 hours may well actually fail between 70 and 200 hours.

C: Plot the results of all tests that have been completed in less than 200 hours and their trend lines on a copy of the master plots for the product

This procedure will generate a marked-up master plot with at least six test results and two trend lines on it within 200 hours (less than nine days).

6.3 *Practical Application*

Consider the sets of test results shown in Figures 10 and 11.

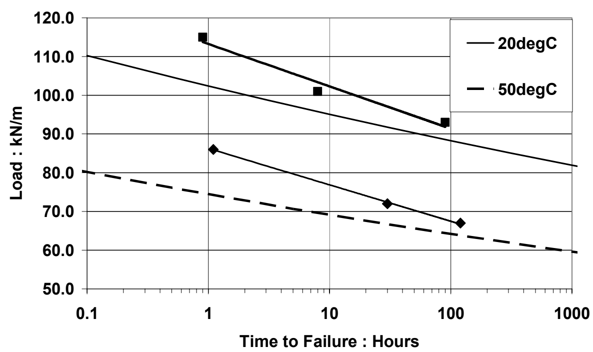


Figure 10: Unacceptable Results

Even though all data points in Figure 10 are well above the master plots, the slopes of the two trend lines are significantly steeper then the master plots. This indicates that different time-shift factors would be needed than those used to generate the master plots. When such a result is found the manufacturer would be free to carry out additional creep tests on the same batch of material to investigate whether the variation was a simple statistical variation between samples.

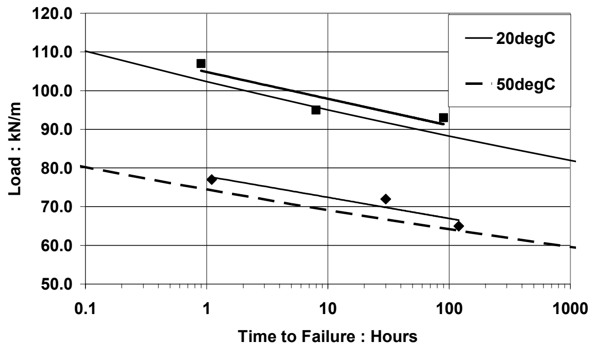


Figure 11: Acceptable Results

In Figure 11 both trend lines are substantially parallel to the master plots and above them. Therefore this would be a set of acceptable results, even though one data point is below the line of the master plot.

7 CONCLUSIONS

7.1 *It is possible to determine the Long Term Design Strength of a geosynthetic through creep testing of around 1000 hours duration.*

For the product range reported here 50 hours of testing at 50^{0}C is approximately equivalent to 10^{6} hours at 20^{0}C. From this and other, unreported, work the authors believe that for polyolefins in general this equivalence lies between 50 hours and 5000 hours. Therefore 1000 hours of testing at 50^{0}C is equivalent to at least 250,000 hours. With such results extrapolation of less than 1 decade will generate 120year predictions. For PET products it will be necessary to use higher temperatures. From the success of SIM testing at elevated temperatures we believe that creep testing up to 70^{0}C would be sufficient.

7.2 *Once a master set of Creep Performance Plots has been generated for a product or a product family satisfactory QA testing can be carried out in less than 200 hours.*

In general, creep testing and the analysis of its results has been a science understood and practised in the past by very few. With simple tools such as the master plots of Figures 9a,b,c and d this science can now be readily used for QA

8 ACKNOWLEDGEMENT:

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