Comparison of different long term reduction factors for geosynthetic reinforcing materials

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ABSTRACT: One hundred fourteen year (10^6h) reduction factors for creep-rupture and for 5% or 10% allowable strain have been determined for polyvinylalcohol, aromatic polyamide, polyamide, polyethyleneterephthalate, polypropylene, and polyethylene geosynthetic reinforcing materials. The creep data were generated using the stepped isothermal method (SIM) for time-temperature superposition(TTS). Since the SIM results are obtained directly, i.e. without extrapolation, we found that three SIM tests are usually sufficient to bracket a single one hundred fourteen year reduction factor for rupture or a single strain limit. This is an important result because it suggests that costs associated with the twelve to eighteen tests needed to develop full creep-rupture curves or the six to twelve tests to generate full isochronous stress vs. strain curves can be avoided in most or many cases. Reduction factors between 1.5 and 3.3 based on rupture, and 1.5 to 4.6 based on a strain limit were obtained for the six materials studied. In both rupture and strain categories the high end was occupied by the polyolefins. The applicability of a rupture based reduction factor where rupture is accompanied by very high strains, e.g. 40% is critically assessed.

1 INTRODUCTION

In the recent past, design reduction factors for one million hour creep phenomena were based on extrapolation of trends established with short and intermediate term (to 10,000 h) tests. It was thought that the accuracy of the prediction could be improved if many tests were performed and the extrapolation based on linear regression analysis with log time the abscissa. The development of the stepped isothermal method (SIM) for time temperature superposition (TTS) has made it possible to shortcut this approach because extrapolations of conventional ambient temperature creep data over a plurality of time decades or the generation of multiple tests at multiple temperatures to establish conventional TTS parameters are no longer necessary to estimate the long term creep-rupture or creep strain status. The assumptions of linear behavior for creep-rupture trends or creep strain curves over extended time periods, while conservative, are not usually appropriate. The semi-log linear model for creep-rupture is based on bond breaking only, which is applicable at high levels of applied stress. When bond formation is considered, which is applicable at lower stress levels and thus longer times, then the model becomes non-linear[Krausz and Eyring (1975)].

In the case of semi-log or log-log plots of creep strain vs. time, it is clear from experiment that the linear, or power law behavior, while useful for many geosynthetic materials, provides a good description only at low stress levels and sometimes only for limited time spans. An important objective of this paper is to demonstrate that using the stepped isothermal method (SIM), often three tests are sufficient to bracket a single million hour reduction factor. This result suggests that the costs associated with the 12-18 tests to develop the full creep-rupture curve or the 6-12 tests for full isochronous stress vs. strain curves can be avoided. In meeting our objective we have generated a survey of creep strain and creep-rupture reduction factors for geogrid products that utilize six different geosynthetic polymers. These are polyvinylalcohol (PVA), aromatic polyamide (Aramid), polyethyleneterephthalate (PET), polyamide (PA), polypropylene (PP), and high-density polyethylene (HDPE). Somewhat extra attention is given to a PVA product family to illustrate the procedures used for all the products tested and to call attention to the similarity of results for product families. The SIM test method has been documented recently as Geosynthetic Research Institute (GRI) Standard Test Method GRI GS10 *Accelerated tensile creep and creep-rupture of geosynthetics based on time-temperature superposition using the stepped isothermal method.*

2 MATERIALS AND METHODS

Table 1 lists the specific products that were characterized for this study. They represent a broad spectrum of material properties that can be mobilized for various reinforcement applications. Included in the table are their glass transition temperatures (T_g) and typical tensile strengths. Rapid loading tensile (RLT), ramp and hold (R+H), and stepped isothermal method (SIM) tests were employed for the test program. The testing was conducted by TRI using predominantly Instron testing equipment. Test procedures have been described in a previous publication [Thornton, et al (1998)].

Table 1. Products tested

Polymer	T_g, °C	Product Designation	Configuration Tested	Typical UTS*	Units
PVA	85	Fortrac M	yarn	1	N/tex
		Fortrac 40M	grid MD	50	kN/m
		Fortrac 80M	grid MD	100	kN/m
		Fortrac 150M	grid MD	200	kN/m
Aramid	340	Fortrac R 150A	grid MD	175	kN/m
PA	50	Fortrac 35MP	grid XMD	25	kN/m
PET	90	Fortrac 35	grid MD	40	kN/m
PP	-20	Fornit 30	grid MD	35	kN/m
HDPE	-20	UX 1400 HS	grid MD	70	kN/m

* Ultimate Tensile Strength using RLT

RLT tests are conducted primarily to obtain an estimate of the ultimate tensile strength of a material being characterized, but also to determine the range of strains that will result as a function of applied stress levels. Very short term creep tests (R+H) and long term creep tests (SIM) are best understood in terms of applied stress expressed as a percentage of the ultimate tensile strength determined at a reference temperature, usually 20°C. Reduction factors for a specific strain limit or for rupture are merely reciprocals of the fractional ultimate tensile strength which when applied to the material will result in the creep limit or rupture at the design lifetime. The utilization of RLT and R+H data to enhance the accuracy of creep strain results has been described recently[Thornton, et al (1999)].

3 RESULTS

3.1 *Polyvinylalcohol (PVA)*

A PVA yarn and three geogrids of various strengths were investigated for this paper. We present details for the yarn and results without details for the geogrids. Figure 1 shows six SIM creep curves for the yarn, three between 55 and 60%UTS and three between 65 and 70%UTS. The three lower curves intersect the 5% strain level just before 114 years; the upper three terminate in rupture, one before and two after 114 years. Figure 2 is an enlarged view of the creep curves after the ramp-up. The 1000s isochrone regression line shown in Figure 3 is used to reposition vertically the creep curves of Figure 1 as depicted in Figure 4. The repositioning of the 5% strain crossing times clarifies the situation, permitting reasonable regression analyses for the yarn as shown in Figure 5. Figure 5 shows regression plots to determine the rupture and strain limited strengths for the 150M grid as well as for the yarn, in bold trendlines. In a faint background plot, 18 ruptures and a rupture trendline obtained for all the PVA products tested is presented.

Similar procedures to those applied to the yarn were followed on the individual PVA geogrids and the results for the yarn and the grids given in Table 2. Note that the variation in the results for the various family members is less than ±3%.

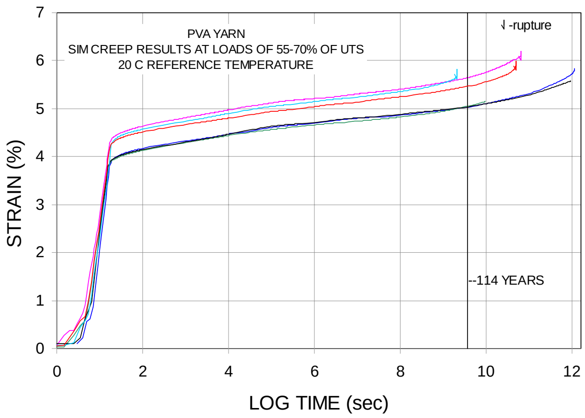

Figure 1. Creep results for PVA yarn

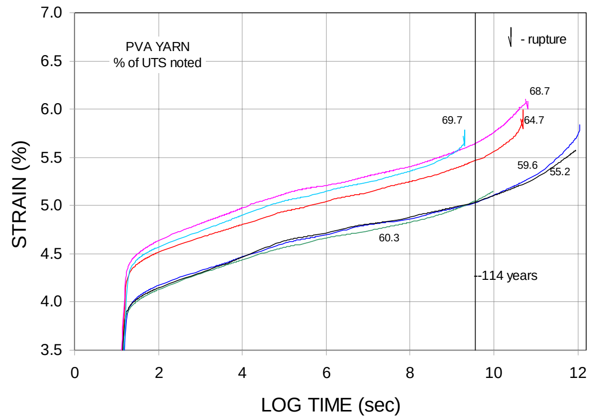

Figure 2. Creep response after the ramp, enlarged from Figure 1

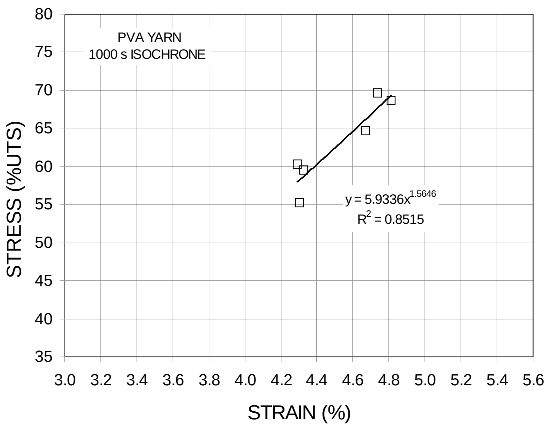

Figure 3. 1000 s isochrone from Figure 1

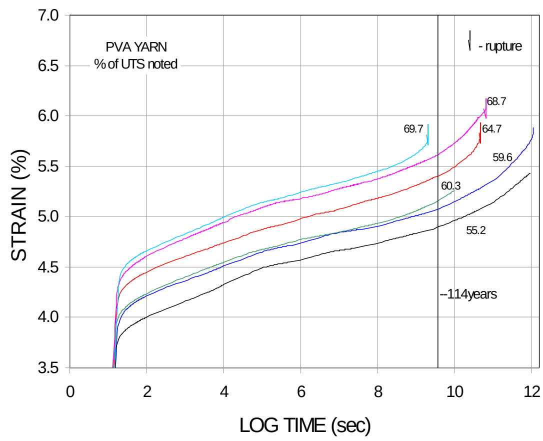

Figure 4. Creep response as in Figure 2, repositioned using Figure 3

Table 2. 114 year creep strain and rupture limits for PVA products

	% of UTS	
	5%Strain	Rupture
yarn	57.44	69.02
40M	61.38	63.73
80M	58.07	65.94
150M	58.12	67.37
Average	58.75	66.53

3.2 *Aromatic Polyamide (Aramid)*

Figure 6 illustrates the creep strain results for an aramid based geogrid. Note that the total strain is less than 2.5% and the time dependent strain is less than 0.5% over 8 decades of time for this very high T_g material. Obviously 5 or 10% creep limits don't apply to this high modulus and creep resistant geogrid. The rupture limit of 67.1 shown in Figure 7 is the highest of the materials tested in the this study.

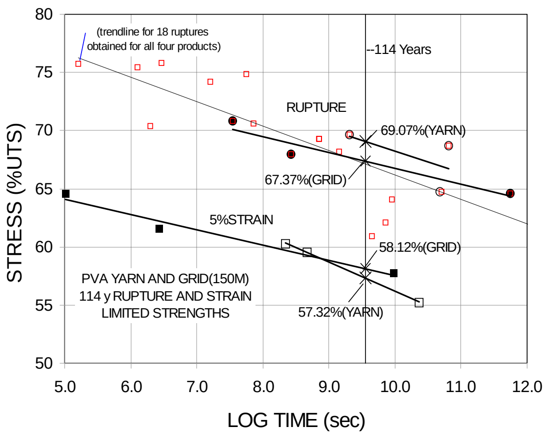

Figure 5. Rupture and 5% strain limited strengths for the PVA yarn and 150M grid

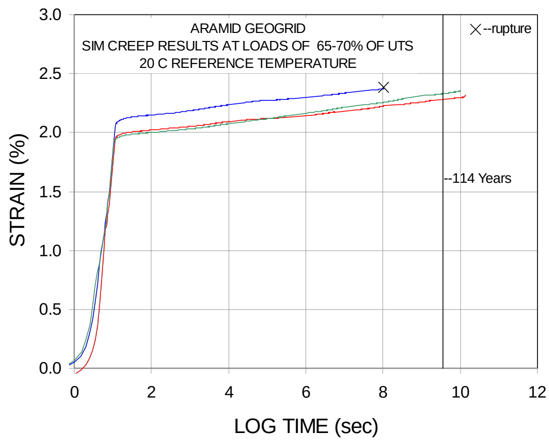

Figure 6. Creep results for Aramid geogrid

3.3 *Polyamide (PA)*

The creep strain curves for the polyamide geogrid are given in Figure 8. It is interesting to note that at the stress levels applied most of the creep occurs prior to 10^5s, which is about 28h. Less than 0.25% net creep is manifest between 28h and 114y. Figure 9 provides the creep and rupture limit regression plots, showing that the creep strain and creep-rupture limited strengths are 44.3 and 50.6% respectively. These strengths are the lowest of the four glassy polymers, those with T_gs above 20-30^O C.

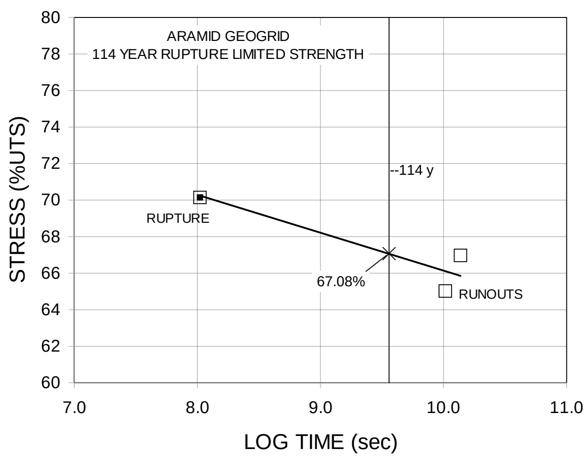

Figure 7. Rupture limited strength for Aramid geog-

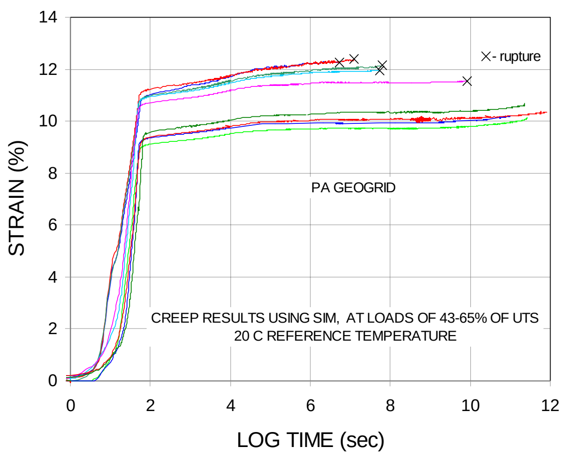

Figure 8. Creep results for PA geogrid

3.4 *Polyethyleneterephthalate (PET)*

Four SIM creep curves and two R+H curve are shown in Figure 10 for PET. The creep loads were between 60 and 64% of UTS. Here the 10% creep strain limit and the rupture limit are virtually indistinguishable. Figure 11 demonstrates that the rupture and strain limits are 62.2 and 61.8% respectively. This particular product was well engineered to rupture at the 10% strain limit.

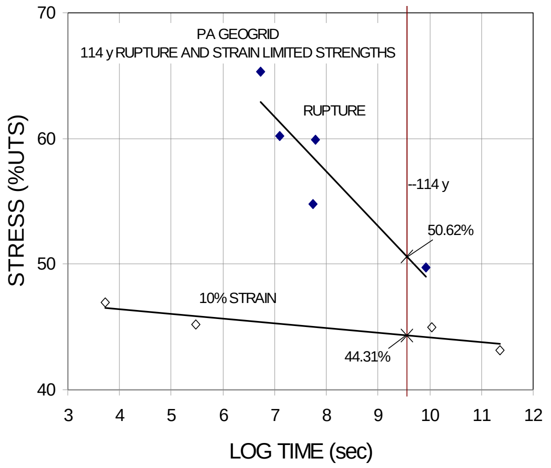

Figure 9. Rupture and 10% strain limited strengths

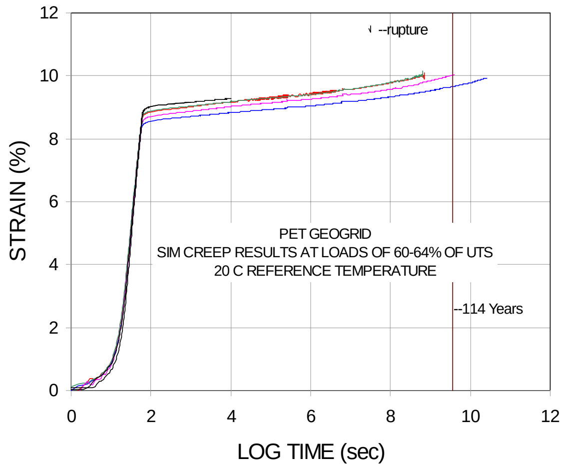

Figure 10. Creep results for PET geogrid

3.5 *Polypropylene (PP)*

Six SIM generated creep curves and one R+H creep curve obtained on the PP at loads of 23-38% of UTS are shown in Figure 12. The R+H curve helps to define a 1000s isochronous stress vs. strain curve which facilitates repositioning the creep curves to get the best possible ordering of them for subsequent analysis of the strain limit. Shown also in Figure 12 are the strain vs. log time traces of rapid loading tensile (RLT) test curves. Note that the rupture strains for the creep curves are three times as great as those for the RLT curves. Since rupture strains do not influence the regression line for rupture, refinement of the strain levels (vertical positions) are not needed for the rupture terminated curves. The regression lines for 10% strain (using the refined data) and for rupture shown in Figure 13 yield 114 year intercepts of 21.6% UTS and 30.5% UTS respectively.

3.6 *Polyethylene (HDPE)*

Figures 14 and 15 present the creep and creep-rupture results for HDPE. There is a pronounced similarity of the creep curves for HDPE to those of PP, but with the HDPE curves requiring slightly higher loads to produce them. The regression plots of Figure 15 show 37.2% and 32.9% of UTS for HDPE rupture and 10% strain limits respectively compared to 30.5% and 21.6% for those of PP. The apparent difference in strain rate for the ramp-up portion of the upper set vs. lower set of 3 curves is due to the difference in temperatures for that part of the tests. The three lower curves (26-34% of UTS) were loaded up at 26°C vs. 20°C for the upper curves (36-41% of UTS). Subsequently the curves which started at 26°C were shifted to 20°C.

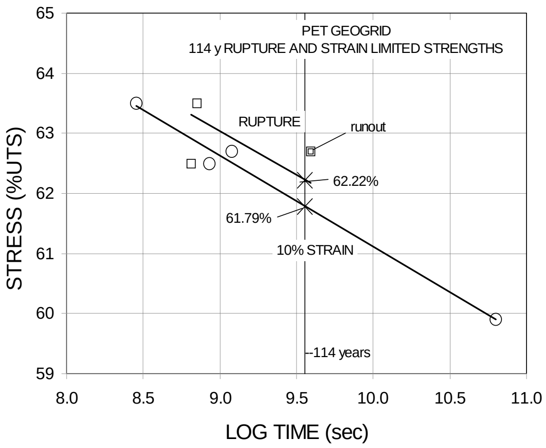

Figure 11. Rupture and 10% strain limited strengths for PET geogrid

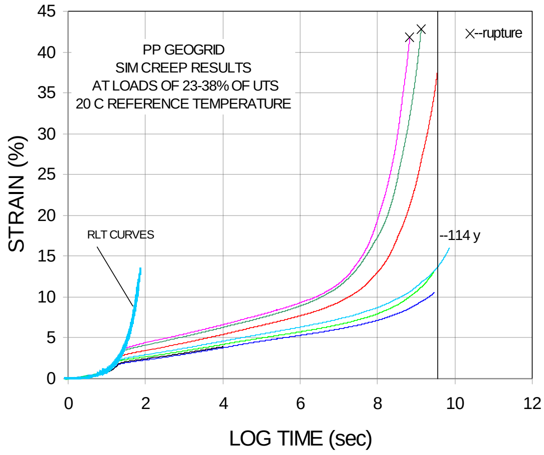

Figure 12. Creep results for PP geogrid

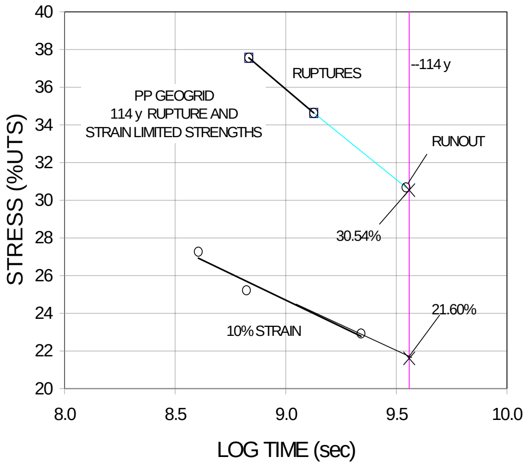

Figure 13. Rupture and 10% strain limited strengths

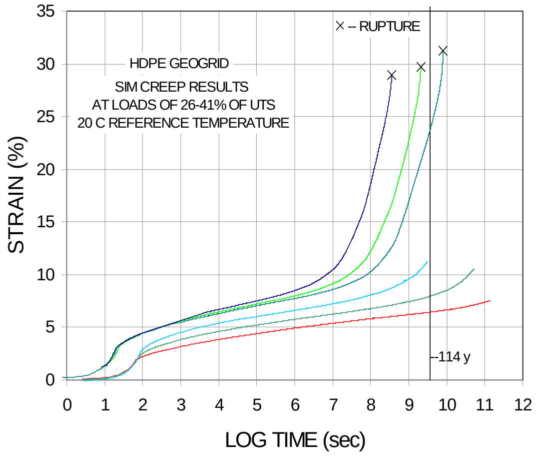

Figure 14. Creep results for HDPE geogrid

4 DISCUSSION OF RESULTS

4.1 *Creep Strain Survey*

Figure 16 provides an overview of the creep strain curves obtained at stress levels just below those resulting in rupture in 1,000,000 hours (114 years) for each of the six materials tested. The strain responses range from 2% for the Aramid to 35% for the PP. Sherby-Dorn plots which are graphs of creep strain rate vs. creep strain for the six curves of Figure 16 are given in Figure 17. Continuously decreasing creep strain rates are necessary for mechanical stability. The decreasing strain rates exhibited by the HDPE and PP indicate mechanical stability but may not be acceptable for design due to the excessive total strain beyond log time 7 (10^7 sec). Creep for both PP and HDPE are nearly second stage (constant strain rate) beyond 10% strain. Note at that the HDPE curve enters the 3rd stage of creep (increasing strain rate) at about 28% strain.

4.2 *Time Dependent Strain Observations*

If one differentiates between the strain developed in the specimen during the ramp portion of the loading history and that developed over the lifetime several interesting features can be noted as shown in Table 3. First of all for PVA and PET, over one-half the time-dependent strain which occurs in 114 years takes place in the first 1000s of the test! The situation is similar for the Aramid material except that the total time dependent strain is less than 0.5% total. With PA, about one-third of the time dependent strain occurs in the first 1000s.

Both of the low T_g polymers display relatively high creep strains, on the order of 30 to 37% at their rupture limited strength levels. For PP the creep experienced beyond 1000s represents 93% of the total and for HDPE 88% of the total. Strains approaching such magnitude could not be tolerated in civil engineering structures.

4.3 *Creep Reduction Factors*

The survey of the results becomes complete with the information collected and presented in Table 4. The range of reduction factors is quite wide. For a typical 10% strain limit, four polymer products provide a range of 1.57 (PET) to 4.63 (PP). At rupture the range is 1.47 (Aramid) to 3.27 (PP). For low strain limit applications both the Aramid and PVA products provide low reduction factors with 1.49 for the Aramid at 2.3% strain and 1.63 for the PVA at 5% strain.

4.4 *Shift Factors for Creep*

Figure 18 displays the logarithm of the shift factors, A_T, used to create the creep curves of Figure 16 for the six polymers of this survey. Of particular interest is the similarity of the curves and the relatively narrow spread of the shift factors for this diverse assortment of polymers and range of Tgs.

Table 3. Ramp and time dependent strain for geogrids of six polymer types at the 114 year rupture limited stress

	114y Rupture Limited Stress, % UTS	Ramp Strain %	Total Strain, % 1000sec	Total Strain, % 114y	Time Dependent Strain, % 0-1000	Time Dependent Strain, % 1000s-114y	Time Dependent Strain, % 0-114y
PVA	69.0%	4.0	4.87	5.65	0.87	0.78	1.65
Aramid	67.1%	1.94	2.05	2.28	0.11	0.23	0.34
PA	50.5%	10.1	10.9	11.57	0.30	0.67	1.47
PET	62.2%	8.3	9.05	9.79	0.75	0.74	1.49
PP	30.5%	1.9	4.35	37.8	2.45	33.4	35.9
HDPE	37.2	2.9	5.26	23.3	2.36	18.0	20.4

Table 4. Creep reduction factors for 114y (10^6h) design life of example geogrids

Polymer (typical UTS)	Strain Limit (%)		Rupture Limit
PVA (50kN/m)	1.63	(5%)	1.57
Aramid (175 kN/m)	1.49	(2.3%)	1.49
PA (25kN/m)	2.26	(10%)	1.98
PET (40kN/m)	1.62	(10%)	1.61
PP (35kN/m)	4.63	(10%)	3.27
HDPE (70 kN/m)	3.04	(10%)	2.69

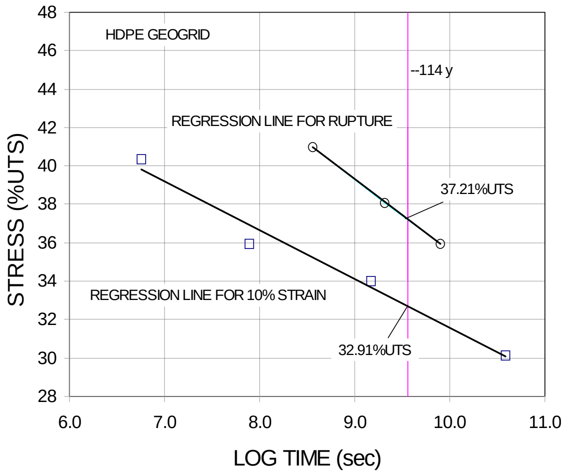

Figure 15. Rupture and 10% strain limited strengths for HDPE geogrid

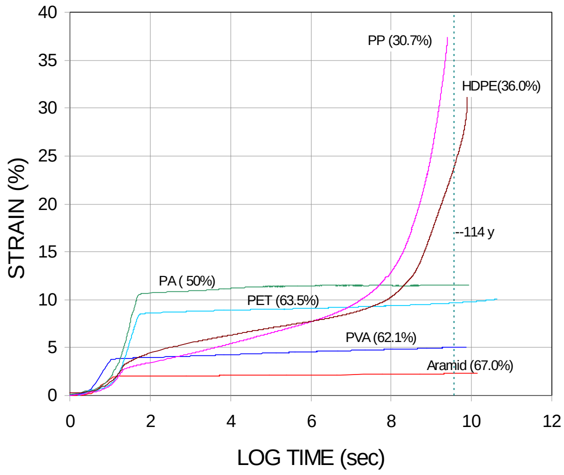

Figure 16. Creep strain survey of six reinforcement polymers. Applied loads (as %UTS) are just under the 114y rupture limit strengths

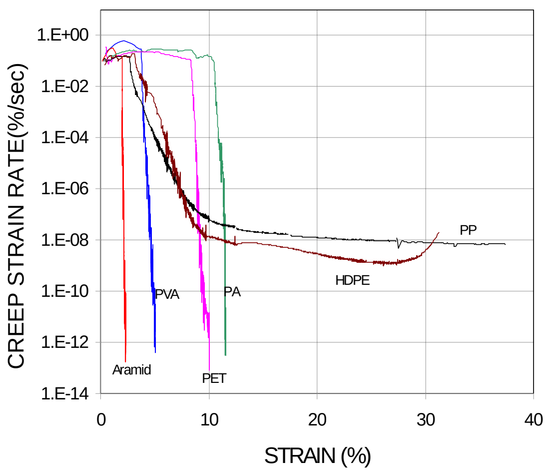

Figure 17. Sherby-Dorn plots for the creep results of

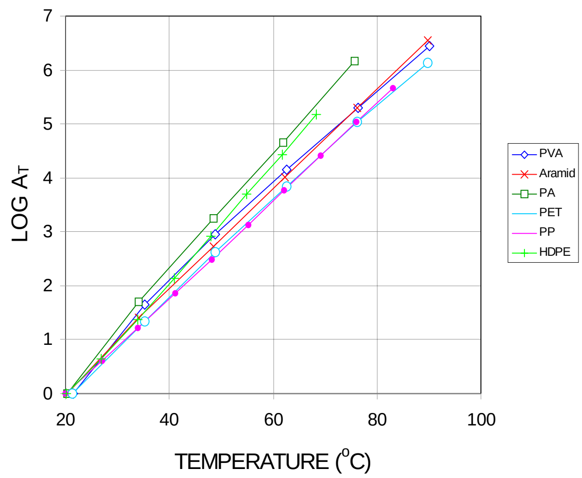

Figure 18. Log shift factors vs. temperature for the creep curves of Figure 16

5 SUMMARY AND CONCLUSIONS

We have demonstrated a procedure for estimating a reduction factor for a strain limit or rupture for a 114 year design life. It appears reasonable that three SIM tests augmented when necessary with one or more short term ramp and hold (R+H) tests are sufficient to suitably characterize a material for one lifetime and one life limiting parameter. Geosynthetics materials with a wide range of properties are available for engineering applications. A 10% strain limit for long life design would not severely limit choice of materials.

ACKNOWLEDGEMENTS

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