Geosynthetics - 7th ICG - Delmas, Gourc & Girard (eds) © 2002 Swets & Zeitlinger, Lisse ISBN 90 5809 523 1

Comparison of SIM and conventional methods for determining creep-rupture behavior of a polypropylene geotextile

J. S. THORNTON, Texas Research International, Austin, TX, USA
T. L. BAKER, Amoco Fabrics and Fibers Co., Austell, GA, USA

ABSTRACT: Baker & Thornton (2001) validated the use of the stepped isothermal method (SIM) for creep of a woven polypropylene (PP) geotextile. SIM results were compared to conventional results, both utilizing time-temperature superposition (TTS). A parallel approach is used here for creep-rupture of a similar product. When several test temperatures are used and creep-rupture results shifted to a reference temperature, ambiguity in the rupture time can arise due to alternative shifting procedures. The present paper examines shifting alternatives including conventional TTS of rupture terminated creep curves, SIM , block shifting of entire rupture curves and the rate process theory as applied to rupture by Zhurkov (1965). Herein, factors for conventional TTS shifted and SIM generated stress-rupture curves are found to be indistinguishable and to depend on both stress and temperature, consistent with the rate process theory, not block shifting. The results validate the use of SIM for creep-rupture of PP geotextiles.

1 INTRODUCTION

Previous work on a woven polypropylene (PP) geotextile (Baker & Thornton, 2001) has demonstrated that creep curves produced using the stepped isothermal method (SIM) of time-temperature superposition (TTS) compare favorably with those using the conventional ambient temperature long-term approach and the conventional elevated temperature TTS approach. Furthermore the shift factors or time acceleration factors used to juxtapose the creep-strain vs. log time curves for SIM and those to superpose the creep-strain curves for the conventional TTS method were found to be equivalent. A slight tendency for shift factor dependency on applied load was noted, but the data density was too small to establish this dependence quantitatively.

The present work considers the topic of creep and creep-rupture as applied to a woven PP product from the same family as employed in the previous effort. The overall objective is to compare several methods for determining creep-rupture master curves to assess their merits and recommend a preferred approach for evaluating the long-term strength of geosynthetics of this type. The methods examined include SIM, conventional ambient temperature (20°C) creep-rupture testing, conventional (TTS) shifting of creep-strain curves, at least one of which results in rupture, and block shifting of sets of elevated temperature rupture data.

With SIM, the times-to-rupture at the reference temperature are derived from the times of the individually shifted, juxtaposed, and isothermal short creep-strain segments obtained at the same loads but at increasing temperatures (Thornton et al. 1998). With conventional ambient temperature creep-rupture testing, the time-to-rupture is unambiguous, since no shifting is needed. In conventional TTS a family of creep-strain curves at the same load but different temperatures are shifted in log time to obtain overlap and form a master curve. In block shifting of creep-rupture load vs. log time obtained at the same elevated temperatures but different applied loads is done to obtain a "best fit" composite creep-rupture curve at the reference temperature. This latter method does not allow for the load dependency of the shift factors, while the strain shifting methods, including SIM, do. Computing the differences in the log of the rupture times for the same loads at different temperatures is done here to generate individual rupture point shift factors that can be compared to those generated by conventional strain shifting or by SIM. However, rupture point shift factors have no predictive value because there is not an established way to shift a higher temperature rupture time other than to a data point or extrapolated regression line established at the same load and a lower temperature.

Free volume and rate process theories offer guidance for organizing the variables associated with TTS of polymeric materials. The most familiar method of shifting data at different temperatures employs the WLF equation. The WLF equation, which can be derived from free volume theory (Ferry 1980), provides a relationship between the test temperature, T, the glass transition temperature of the polymer, T_g, and the log of the shift factor, a_T, as follows:

$$\text{Log } a_T (T, T_g) = \frac{-17.4 (T - T_g)}{51.6 + T - T_g} \quad (1)$$

where 17.4 and 51.6 which have been referred to as "universal" are constants that are found to work for many polymers. In this form a_T is the ratio of the relaxation or retardation process rates occurring at T_g and T. When the test temperature is above the glass transition temperature, log a_T in Equation (1) is an attenuation factor. An acceleration factor, A_T, which is the reciprocal of a_T can be defined for a reference temperature, T_R(usually 20C), which is generally below the test temperature. This yields:

$$\text{Log } A_T (T_R, T_g) = \frac{17.4 (T_R - T_g)}{51.6 + T_R - T_g} \quad (2a)$$

for the shift between T_g and T_R , and:

$$\text{Log } A_T (T, T_R) = \frac{17.4 (T - T_g)}{51.6 + T - T_g} - \text{Log } A_T (T_R, T_g) \quad (2b)$$

for the shift between T and T_R. WLF does not anticipate a load dependence of the shift factor since it applies to linear viscoelastic behavior, which is realized in plastics only at low strains (a few tenths of a percent). Rupture, of course is a large strain phenomenon in the polymer of interest here. Smith (1962) has used WLF shift factors to organize rupture data for certain elastomers, despite their nonlinear behavior, but since the elastic modulus, E, of an elastomer is small compared to its bulk modulus, K, Poisson's ratio, μ=[3K-E]/6K~0.5. Hence, tensile loads do not produce much dilation in these materials. Since dilation is expected to enhance molecular mobility, the expected load dependence of creep in plastics (where $\mu < 0.5$) may not be significant in elastomers. Takaku (1980) found that load independent WLF factors worked to form master rupture curves for drawn polypropylene films, but the range of experimental times and stress levels was too limited to display a stress dependence. However his log-log creep-rupture curves showed negative curvature which could be attributed to an unresolved stress dependence (see below, Figure 4f).

Smith (1962) originated the idea of a time and temperature independent "failure envelope" which is a rupture stress vs. rupture strain plot for an individual material of all rupture data generated in a testing program. These could include creep, stress relaxation, constant strain rate tensile, and constant load rate tensile testing data. Smith suggested that for time-temperature equivalence to be valid, the data so plotted should form a simple continuous function. A "Smith Plot" is provided in section 3.

Zhurkov (1965) examined the times to failure of small specimens of 50 different materials, including metals, alloys, ionic solids and polymers under constant true stress and confirmed the broad applicability of rate process theory to the initiation of rupture of solids. For small specimens, rupture and rupture initiation times are the same. Zhurkov proposed the following expression for the time-to-rupture, τ:

$$\tau = \tau_o \exp\left[(U_o - \gamma\sigma)/kT\right] \quad (3)$$

where U_o is the activation energy for the bond breaking process, γ is a factor with units of volume, related to stress concentration, σ is the applied stress, k is Boltzman's constant, τ_o is the period of atomic vibration($\sim 10^{-13}$ s) and T is the temperature. U_o and γ are considered to be independent of temperature and stress. From this relationship another shift factor, A_T, can be defined as the ratio of times to rupture between a reference temperature, T_R, and the test temperature, T, at a constant stress, σ. Log A_T derived from Equation (3) is:

$$\text{Log } A_T = \frac{U_o - \gamma\sigma}{2.3\,k}\left(\frac{1}{T_R} - \frac{1}{T}\right) \quad (4)$$

where again, $T_R < T$. Note that the shift factor is reduced for increasing stress.

2 MATERIAL AND METHODS

2.1 *Material*

For this study a woven polypropylene geotextile was used. All of the tests performed were in the fill (cross machine) direction of the fabric. The fabric uses a fibrillated fill yarn. The average ultimate tensile strength (UTS) of the specimens tested was about 52kN/m with and average strain at ultimate of 10.6% under rapid loading conditions.

2.2 *Test procedures*

Over 100 creep tests including 15 SIM tests with test durations of 1 minute to 10,000 hours were performed at ambient and elevated temperatures, with 81 tests taken to rupture. Some tests at relatively low load levels were taken to times just sufficient to establish the shift functions, log A_T, to superpose the strain vs. log time plot. All of the tests performed were constant load, as is the convention in the geosynthetics industry. Strain readings were made throughout all of the tests to allow the superposition of the strain vs. log time curves, which can include one or more time-to-rupture points. Frequently, studies of time-to-rupture have ignored superpositioning of strain vs. log time or modulus vs. log time plots and just focused on the time-to-rupture by itself. Matching by overlaying of the strain curves at different temperatures is fundamental to the original concept of TTS.

In many creep and creep-rupture studies of geosynthetic products, cost constraints dictate minimal duplication of load levels at the different temperatures. Often fewer than 50% of the load levels tested at one temperature will be repeated at the next higher temperature. This may obscure trends in the data and disguise mismatches in the slope of the rupture curves at different temperatures. In our work, to the extent that it was possible, tests at a given load level were performed at each temperature to provide the maximum possible overlap of the time-to-rupture plots. About 70% of the load levels tested at 20°C were repeated at all of the temperatures and over 80% of the load levels at any given temperature were duplicated at the next highest temperature.

The conventional tests at ambient and elevated temperatures were either performed using a 200mm wide strip with a lever applied dead load, or using a 50mm strip loaded in a universal testing machine. Tests were performed at 20°, 40°, 60° and 80°C. The temperature was controlled to within ±1°C during the course of the tests. The SIM tests were performed and analyzed as given in Thornton et al. (1998). For the SIM tests 50mm wide specimens were used exclusively. The SIM tests were projected from a 20°C starting point and because of previous results (Baker & Thornton 2001) it was anticipated that the SIM results could be combined with the 20°C ambient test results in the development of some conclusions of this study. This turned out to be true, which expanded the number of estimates for the rupture time shift factors that could be related back to 20°C. Replicate tests were performed for many of the combinations of load level and temperature.

Throughout this paper the results are expressed in terms of load level as a percent of the ultimate tensile strength (% UTS) as determined at 20°C by a constant rate of extension tensile (10% per minute) test. Test specimens were identified and grouped such that all specimens in a group were cut on the same fill yarns. To provide more precise control of creep test load, at least one set of tensile tests was performed for each specimen group. The tensile tests were performed using the same width and length specimen as that used in the creep test.

2.3 *Vertical shifting of initial creep strains*

The strain variability usually encountered in creep testing is a manifestation of the initial strain value at the peak of the loading ramp. Replicate creep tests demonstrate that the increase in creep-strain with time after that initial value is reproducible. Thus, if the initial strain value is determined by vertical (strain) shifting to the mean value of multiple tests, the long-term creep-strains will form a relatively tight pattern (Thornton et al. 1999). Extensive use of very short term (~1000s) "ramp and hold" creep tests has been employed herein to improve data quality. With this approach, the creep strains at 1000s are averaged.

2.4 *Regression analysis*

The rupture data is presented graphically with rupture strength (or log rupture strength) as the ordinate and vs. log time as the abscissa, which is conventional practice in the geosynthetics community. However, the regression computations are conducted with rupture stress as the independent variable.

2.5 *Conventional shifting of strain data*

The conventional way to obtain creep-strain based-shift factors starts with a plot of the creep-strain vs. log time curves for a given load level for the 20°C reference temperature and the 40°C, 60°C and 80°C elevated temperatures. Next, each of the elevated temperature curves is moved along the horizontal log time axis to longer times until it superposes on the 20°C curve as neatly as possible. The resulting overlaid structure is the master creep curve. Figure 1 illustrates this process. The horizontal distance that each elevated temperature creep curve is moved to achieve superposition is the log of the shift factor for that temperature. Using this procedure, relatively long-term creep-rupture times can be projected by superpositioning a sequence of elevated temperature creep tests in which one or more results in rupture.

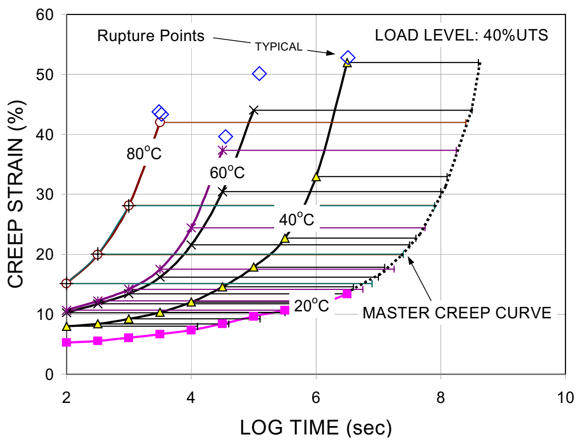

Figure 1. Horizontal shifting to achieve a master creep-curve

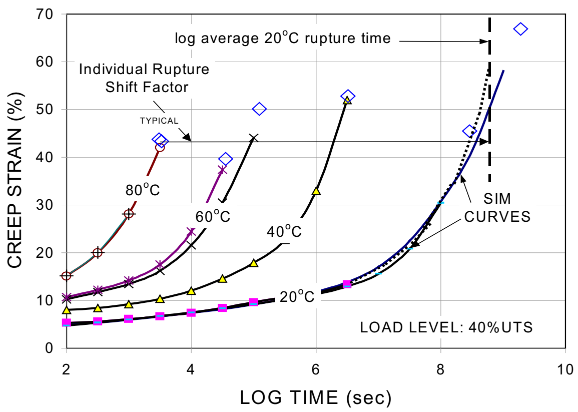

Figure 2. SIM curves with 20°C rupture points added to the data of Figure 1 to permit measurement of individual shift factors

2.6 *SIM shifting*

SIM is a special case of TTS involving the juxtaposition of creep-strain curve segments to achieve the master curve. The creep-strain segments are generated in a series of isothermal dwells at progressively increasing temperatures. The creep-strain segments are prepared for joining to make up the master curve of creep-strain vs. log time, 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. 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. The horizontal distance that each segment is moved relative to the curve for the reference temperature is the log of the shift factor for the temperature of that segment. This process is described in more detail in Thornton et al (1998).

2.7 *Block shifting of rupture curves*

Block shifting of the entire rupture curves developed at different temperatures to generate the master rupture curve can only lead to valid results if the curves are truly parallel. For small data sets this may be a necessary assumption because of lack of load level duplication at the different temperatures to test its validity.

2.8 *Shifting of creep-rupture data points*

It is straight-forward to compute the ratio of rupture times or difference in log times-to-rupture for creep-rupture tests at different temperatures to generate "shift factors" for those events. However as discussed above, such shift factors can't be used to generate master curves, only to provide comparisons with other shift factors that can. To illustrate, Figure 1 shows five rupture data points, two at 80°C two at 60°C and one at 40°C. Since the 20°C curve in this figure does not culminate in rupture, it is not possible to obtain shift factors that project forward beyond the 40°C point. Figure 2 adds three SIM curves with two rupture times to Figure 1 and as a result, the shifts between the log average 20°C rupture time and the elevated temperature rupture times can be obtained readily.

3 RESULTS AND DISCUSSION

3.1 *Empirical results*

The results of all the creep-rupture tests performed in this investigation are presented as (log) rupture strength (%UTS) vs. log time (seconds) in Figure 3. Other than the SIM results, which represent individually shifted master curves, the results are unshifted. The linear regression lines for this chart, suggest that log-log plots will represent the data appropriately. Table 1

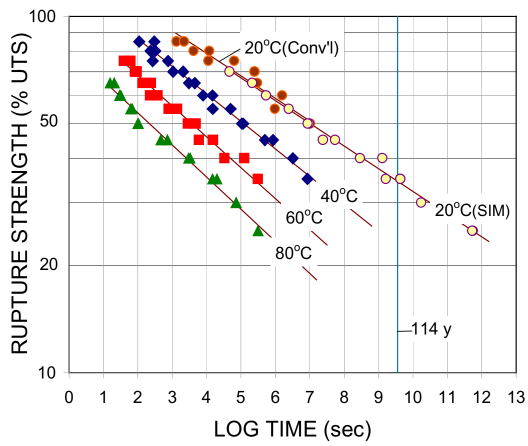

Figure 3. Creep-rupture curves for conventional test results at ambient and elevated temperatures, and for SIM results referenced to 20°C

presents a compilation of the slopes (power law exponents), the log time = 0 (1 sec) intercepts, log time = 9.5563 (114 y) intercepts and the R^2 values for the regression lines of Figure 3. A comparison of the regression parameters for conventional ambient (20°C) temperature and SIM tests shows that the regression lines are nearly parallel (0.0632 vs. 0.0638 respectively) and the 114 y intercepts (35.13% vs. 34.42%) are less than 1% apart. The individual regression lines for those two populations shown in Figure 3 are nearly indistinguishable. The elevated temperature results of Figure 3 are convincingly linear, but the curves are clearly not parallel with each other or the 20°C and SIM curves. Apparently, the combined effect of temperature and stress on the rupture times is greater than would be the case if the influence of temperature and stress were independent. In other words, the shift factor between the rupture curves for different temperatures appears to also depend on stress. This is the type of behavior anticipated by the rate process theory and is why block shifting might not work well for this material at least under some conditions.

Figure 4 presents a stack of 6 regression plots representing various ways of presenting the results of Figure 3, and Table 2 presents the accompanying regression parameters. Plots (a) and (b) of Figure 4 and the top two lines in Table 2 are for SIM alone and SIM combined with the conventional 20°C rupture results. The 114 y intercepts of 34.42% and 34.44% UTS are essentially identical. Of course, with a few more data points and with longer reach, the SIM results would be expected to dominate the combined regression results. SIM data is excluded from plots (c)–(f).

Table 1. Regression parameters for Figure 4

Line	Power law exponents	Intercepts, % UTS 1 sec	114y	R^2
20ºC	-0.0632	141.19	35.13	0.9229
SIM	-0.0638	140.06	34.42	0.9903
40ºC	-0.0773	123.40	22.53	0.9833
60ºC	-0.0868	102.13	15.13	0.9742
80ºC	-0.0902	81.23	11.16	0.9857

Table 2 Regression parameters for Figure 5

Line	Power law exponents	Intercepts, % UTS 1 sec	114y	R^2
SIM	-0.0638	140.06	34.42	0.9903
20°C+SIM	-0.0646	142.70	34.44	0.9833
Strain	-0.0662	144.04	33.54	0.9876
Block (linear)	-0.0811	173.25	29.12	0.9727
Block (non-linear)	N/A	N/A	28.00	0.9756
Block (WLF)	N/A	N/A	37-39	0.95-0.91

Plot (c) shows the results of the Strain Shift process. As discussed above the shifting procedure involves the superpositioning of the creep-strain curves, with the rupture time being carried forward as a result. Here the slopes and 1 sec intercepts of the isothermal data both change with shifting, so that each of the curves after shifting as well as the overall composite or master curve point to a realistic 114y intercept. Table 2 provides an overall 114y strength estimate of 33.54%UTS.

The Block Shift (linear) curve, given by plot (d) Figure 4, displays the results of block shifting the elevated temperature rupture curves onto the 20°C rupture curve. The procedure used here was to assume that all four regression lines of Figure 3 were parallel, taking the form:

$$\sigma = A + B\,(\log t + C_i\,[T - 20]) \qquad (5)$$

where C_i represents the set of shift factors from the elevated temperature curves to the 20°C curve. The Excel Solver utility was used to evaluate the block shift factors that maximized R^2 for the shifted population. The 114 year intercept for the overall regression line is 29.12%.

The Block Shift (non-linear) plot (e) is similar to plot (d) except that (e) is a second degree polynomial fit to the data rather than linear, and as such, the shift factors to optimize R^2 differ slightly. The non linear regression plot is suggested as a way to explain the results of Takaku (1980) which show a negative curvature possibly due to unresolved stress dependence.

Plot (f) of Figure 4 was generated by block shifting using the universal WLF shift factors as computed from Equation (2b) with T_g taken as 0°C. Both linear and polynomial trend lines are computed for the resultant array of rupture data. The fits of the linear and polynomial trend lines are comparatively poor with R^2 of 0.9121 and 0.9509 and 114y intercepts of 38.62% and 36.91% respectively.

The SIM, 20°C+SIM and Strain Shifted regression curves correlate well, as do the Block Shift (linear) and Block Shift (non-linear) curves. But the two systems of shifting do not. The former intercepts average 34% compared to 29% for the latter. The WLF Shift (universal) results stand apart from the others and in a comparative sense, don't seem to describe the data well enough to consider seriously.

As mentioned above, empirically derived shift factors for the horizontal translation of individual rupture times from elevated temperature positions to positions along the reference temperature rupture line can be determined after the position of the reference temperature line is established. The result of this is not displayed separately since it would be identical to the plot

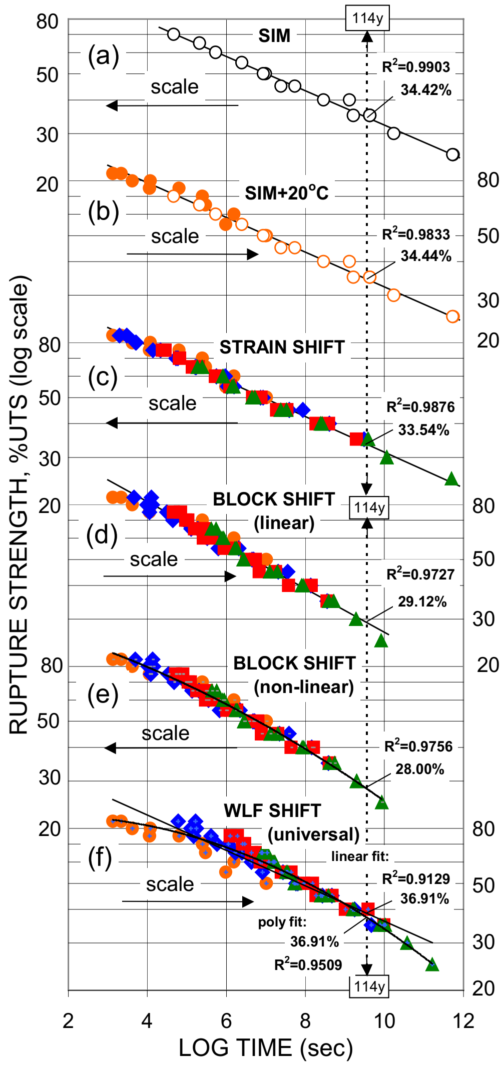

Figure 4. Creep-rupture master curves at 20°C reference temperature for (a) SIM; (b) SIM combined with conventional 20°C data; (c) strain shift of sets of creep curves containing one or more rupture points; (d) block shifts of elevated temperature rutpure curves optimized for a linear (log-log) fit; (e) block shift as (d) except optimized for a polynomial fit; (f) block shifts using the universal WLF factors showing both linear and polynomial trend lines.

chosen to represent the reference temperature data. The 20°C+SIM curve, is the most reasonable, given that it's the only one that didn't utilize, for its generation, the conventional elevated temperature rupture data that is to be shifted.

3.2 *Summary of the empirical shift factors*

Figure 5 presents the shift factors generated from the data: SIM and Strain Shifts both employ matching creep-strain curves to obtain individual long time rupture points; Block and WLF Shifts both use the elevated temperature regression lines to generate the long term composite relation; and finally the Rupture Shifts are measures of the horizontal translation of individual rupture times to the 20°C+SIM regression line. The SIM and Strain Shift data correlate well with the Rupture Shift data, all of which display stress as well as temperature dependence. The Block Shift and WLF Shift results show only temperature dependence, by design. The linear and nonlinear Block Shift factors are within 1% of each other, within the range of variation of the other results.

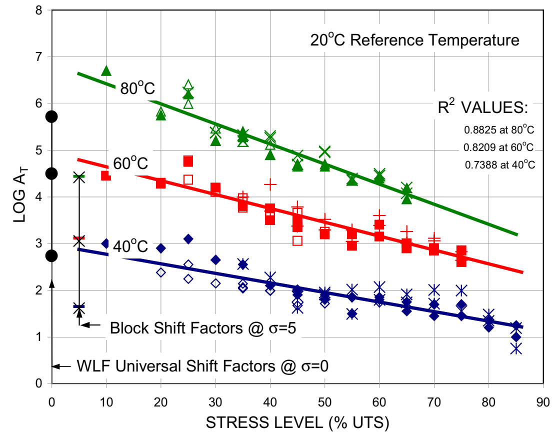

Figure 5. Stress dependent log time shift factors of Figure 4: Open symbols, SIM; filled symbols, strain shifts; stick symbols, individual rupture times. Stress independent factors: Block shift linear, x and non-linear, bar at σ = 5%; WLF universal, filled circles at σ = o.

3.3 *Smith Plot*

Rupture stress-strain pairs determined at different temperatures and rates of stress or strain application are connected to generate a failure envelope called a Smith Plot. Increasing creep or load application rates, or decreasing test temperatures move the rupture stress-strain points in a counterclockwise fashion starting from a point associated with the slowest strain rate and the highest temperature. According to Smith (1962), this type of behavior is required for time-temperature equivalence to be applicable to rupture data. Between the origin and the point just described is the equilibrium stress-strain curve, a theoretical boundary below which rupture should never occur. Smith developed this idea for amorphous elastomers, but it is not uncommon in the practice of materials engineering to encounter rupture data plotted for plastics this way. Figure 6 is the failure envelope relating the rupture strengths of all the data to their companion rupture strains. Included on this envelope are a few constant loading rate rupture points which suggest the envelope may be independent of the type of test performed in addition to being independent of temperature and time. An estimated equilibrium stress-strain curve is plotted below the rupture data. This curve is based on 10^{11}s isochronous data obtained from the creep-strain master curves, but reduced by 5%UTS to point the low stress-strain end of the curve at the origin. This curve is consistent with a plausible placement of an isochrone at 10^{12} or 10^{13}s (30,000 to 300,000 years).

3.4 *Comparison to rate process theory*

The data of Figure 4 are presented in a semi-log format in Figure 7. The data can be described as linear above 45%UTS but noticeably nonlinear below that number. The rupture times investigated by Zhurkov (1965) were somewhat shorter than those encompassed in Figure 7. Zhurkov observed such nonlinear performance at lower stress levels which he attributed to a bond mending process not considered in the rate process model. A strict application of Zhurkov would require a temperature independent activation energy, U_o, and a stress independent activation volume, γ. However, given that the data set of the present work was obtained at constant load rather than constant stress and that the opinion of some authors such as Barton and Cherry (1979) is that U_o and γ have temperature and stress dependence, a lenient application of Zhurkov must be tolerated, but is not without considerable value. The straight lines of Figure 7 are fit to Equation (3) where U_o and γ are permitted to vary as shown in Figure 8. Equation (3) predicts

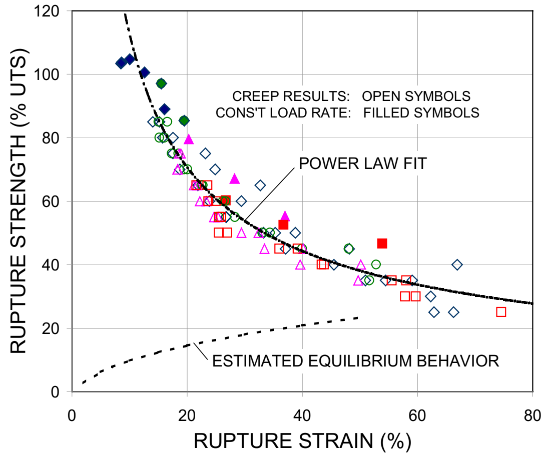

Figure 6. Smith Plot of rupture stress-strain pairs for creep tests and for constant loading rate tensile tests at all temperatures and strain rates. The equilibrium stress-strain curve is estimated from isochronous data.

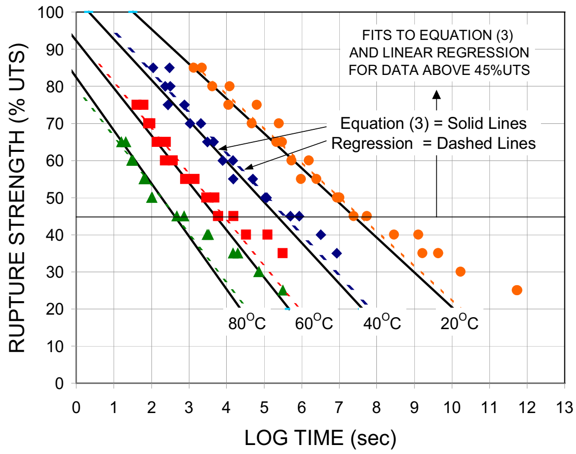

Figure 7. Creep-rupture results for strengths at and above 45%UTS fit to Equation (3).

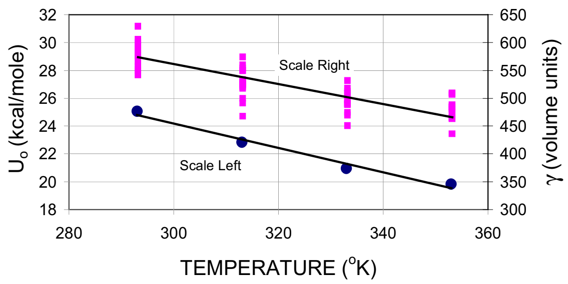

Figure 8. Temperature dependence of the activation energy and activation volume for the lenient fit of Equation (3) to the rupture data.

that the rupture strength vs. log time curves will converge to a pole at a stress level where thermal fluctuations are not needed to produce rupture. This stress level will correspond to an acceleration factor of unity (log A_T = 0). Figure 9 illustrates the convergence of the lines of isothermal rupture strength vs. log time at about 175%UTS and $10^{-6.5}$ sec. Figure 10 repeats the load dependent shift factors previously presented in Figure 5 except that the regression lines are replaced by log A_T computations using Equation (3). A comparison of Figures 5 and 10 shows that Equation (4) represents the empirical shift factors nearly as well as the regression lines. The intercepts of the 80°C, 60°C and 40°C regression lines of Figure 5 with the log time axis at $\log A_T$=0 are at 142%, 160%, and 168%UTS

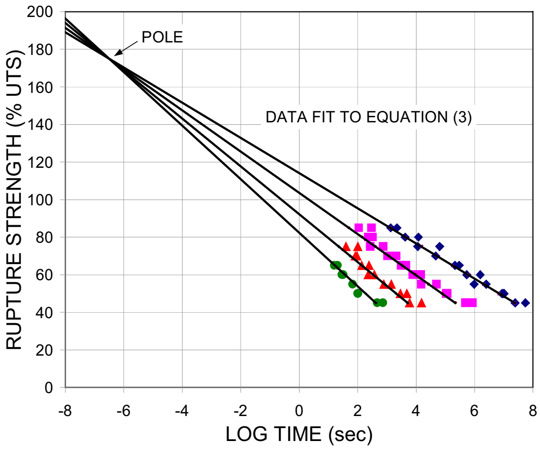

Figure 9. Similar to Figure 8, showing the pole of convergence at 175%UTS and $10^{-6.5}$ sec.

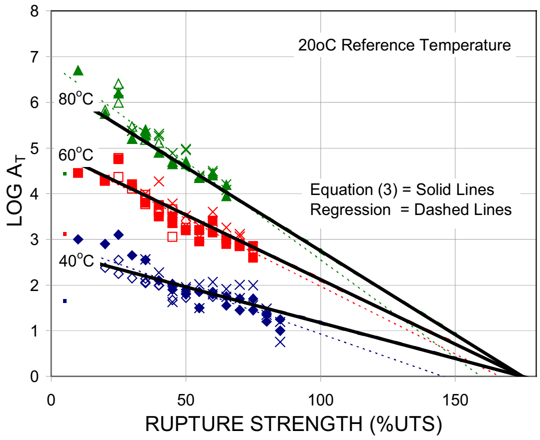

Figure 10. Similar to Figure 5, showing the fit to Equation (4) the pole of convergence of the log shift factors at 0 and 175%UTS. The dashed regression lines are the same as the solid lines of Figure 5.

respectively. This compares to the $\log A_T=0$ pole at 175%UTS. While admittedly a lenient fit to Zhurkov's model, the fit of experimental results strongly support the idea that stress dependent shift factors for temperature best describe the long term creep-rupture behavior of the subject polypropylene material.

4 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions apply to the fill direction yarns of the polypropylene geotextile material investigated:

1. Horizontal shifting along a log time axis to achieve composite master compliance or modulus vs. log time curves is the original concept of TTS, and remains the fundamental concept of TTS.
2. SIM depends on the original TTS concept, and produces results in excellent agreement with conventional ambient temperature (20°C) creep test results and with master curves produced by horizontal (log time axis) shifting conventional elevated temperature creep test results to superpose the 20°C results. The SIM is recommended as the preferred approach for evaluating long term creep response of these PP textiles.
3. The best fit of the conventional ambient and elevated temperature creep-rupture data was obtained by individually shifting the time-to-rupture data points using the same shift factors as developed for the creep-strain master curves. This strain shifting procedure is in accordance with the fundamental concept of TTS and not in violation of rate process theory. The strain shifting approach is the gold standard for TTS and is recommended as a reserve procedure if confirmation of SIM predictions should be needed.
4. A conservative result was obtained by block shifting using empirical factors as compared to SIM and conventional TTS shifting. This was found for both linear and non-linear regression line optimizations. With data sets more limited than those generated here, the degree of conservatism could be small. However, the slopes of the 60 and 80°C rupture curves are steep and the results of small data sets shifted in this way could lead to unacceptable conservatism Block shifting violates the stress dependence of the time shift predicted by rate process theory.
5. The WLF concept of universally applicable shift factors, dependent only on test temperature and pressure, and the glass transition temperature of the polymer, is limited to linear viscoelastic behavior. At stresses and strains of practical value (above a few % stress and a few tenths % strain) polymer viscoelastic performance is nonlinear. Shifts of the elevated temperature linear regression lines using the universal WLF factors were relatively poor, and the results not conservative.
6. The experimental data supports the concepts of the rate process theory as expressed by Zhurkov, that the effect of temperature on the times-to-rupture depends heavily upon the level of load applied. This means that the shift factor for TTS will depend on load level as well as temperature. The rate process model predicts that creep-rupture curves generated at different temperatures will not be parallel. However, a full Zhurkov creep-rupture characterization is not economical.
7. The SIM, which is purely empirical and shown to be valid herein, is recommended for obtaining long term creep response and rupture performance data on polypropylene products.

ACKNOWLEDGEMENT

The authors express appreciation to their employers, Texas Research International, Inc. and the Amoco Fabrics and Fibers Co. for providing the facilities and support for their joint efforts to make this paper happen.

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