COMPARISON BETWEEN STEPPED ISOTHERMAL METHOD AND LONG-TERM CREEP TESTS ON GEOSYNTHETICS

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ABSTRACT: The results of long-term creep tests in air, lasting for up to 14 years, on polypropylene, polyethylene and polyester reinforcing geotextiles are compared with the predictions from accelerated tests under the same loads using the stepped isothermal method (SIM). For three of the four materials tested, the data from SIM tests provide reasonably accurate to good predictions of the actual strain. The accuracy of the predictions were noticeably poorer for a heavy woven polypropylene. For a sheathed polyester strip, the creep-rupture characteristic, the design loads and creep reduction factors predicted using SIM agree well with those predicted from conventional tests. It is recommended that ramp-and-hold tests should be used to allow for variability in the initial strains upon loading, and that 1000 hour long tests be used to confirm the initial course of the creep curves.

1 INTRODUCTION

Between 1987 and 2002 a number of long-term creep tests on reinforcing geotextiles were performed, initial results from which were published by Greenwood (1990), Watts et al (1998) and Greenwood et al (2000). The final duration of the longest test was 122374 h, or just less than 14 years.

The stepped isothermal method (SIM) is a method of predicting the creep behaviour of a geotextile by time-temperature acceleration.

In this paper the results of the long-term creep tests are compared to those derived from accelerated tests using SIM.

2 MATERIALS

Details of the materials used in this study are given below - the reference system is the same as used in Greenwood et al (2000).

P1: Polypropylene fabric Terram W20/4 received 1987. Plain weave, 570 g/m², tensile strength 206 kN/m in warp direction.

P2: Polypropylene fabric Lotrak 45/45 received 1987. Plain weave, 240 g/m², tensile strength 49 kN/m in warp direction. The sample used for the SIM test had been recovered from an installation damage trial, but it had not suffered any noticeable damage.

P5: *Polyethylene grid Tensar SR2* received about 1987. Tensile strength 77.2 kN/m. (Note that this is not the same as material P5 referred to by Watts et al (1998), which was Tensar SR80.)

P6: Paraweb strip comprising parallel yarn bundles sheathed in low density polyethylene, 90 mm wide, supplied on 6 January 1993. Tensile strength 58.5 kN. Note that the loads for P6 are quoted in kN for the strip and not in kN/m: the strength of the corresponding Paralink 300 M product, which made up of woven strips (5.56 strips per metre width), is 325 kN/m.

3 TEST METHODS

The methods used for the conventional long-term tests have been described in Greenwood (1990), Watts et al (1998) and Greenwood et al (2000).

The SIM tests were performed to an ERA in-house UKAS accredited procedure which is based on the two publications by Thornton et al (1998) and the commentary by Greenwood and Voskamp (2000). For these tests, 35 mm diameter roller (capstan) grips were used for P1 and P2, flat plate grips for P5, and 50 mm diameter roller grips for P6. The gauge length for the SIM tests was 60 mm except for P5 where it was 115 mm. The loads were chosen so as to equate as closely as possible to those used in the conventional tests. Since the equipment for SIM was restricted both in terms of the loads it could carry and in the space available in the temperature cabinet, narrower samples were used for these tests than for the conventional creep tests; the applied loads were in proportion to the number of yarns in the direction of loading. The SIM tests on P6 were performed on one of the ten yarn bundles making up a strip. All tests were performed in air.

In all the SIM tests, except those undertaken on P5, the temperature steps were 14ºC, up to a maximum temperature of 90ºC, and the temperature shift factors ranged from 0.07 to 0.09 decades per ºC. For the SIM tests on P5 the temperature steps were 7ºC, up to a maximum temperature of 62ºC, and the temperature shift factor was 1.4 decades per ºC.

Details of the various tests are as follows.

Material P1: applied load 56 kN/m (27% of short-term tensile strength). The conventional test was terminated after 122374 h whilst the SIM test was terminated after 3 h at 90ºC - equivalent to 340000 h. In neither test did the specimen rupture.

Material P1: applied load 114 kN/m (55% of tensile strength). The specimen in the conventional test ruptured after 9985 h. The SIM test was terminated after the equivalent of 23340 h when the strain transducers reached the end of their range.

Material P2: applied load 15 kN/m (31% of tensile strength). The conventional test was terminated after 121175 h, whilst the SIM test was terminated after 3 h at

90ºC - equivalent to 480263 h. In neither test did the specimen rupture.

Material P2: applied load 25.5 kN/m (52% of tensile strength). The specimen in the conventional test ruptured after 23109 h, whilst the specimen in the SIM test ruptured after the equivalent of 49000 h under load.

Material P5: applied load 31 kN/m (40% of tensile strength). The conventional test was terminated after 113179 h whilst the SIM test was terminated after 3 h at 62ºC - equivalent to 4800000 h. In neither test did the specimen rupture.

Material P6: in total, fourteen conventional tests and eight SIM tests were undertaken, all but one of which ended with the rupture of the specimen. The results of these tests are summarised in Table 1.

Table 1 Results of creep-rupture tests undertaken on P6

Conventional creep-rupture tests				
Load (kN)	% tensile strength (σ)	time to rupture *t* (h)	strain after 1 h (%)	final strain (%)
46.8	80%	159	9.92	11.53
46.8	80%	174	9.92	11.46
45.04	77%	190	9.12	11.23
45.04	77%	303	9.15	9.85
45.04	77%	550	9.10	10.11
45.04	77%	777	9.20	10.89
45.04	77%	795	8.82	10.54
45.04	77%	828	8.99	10.69
45.04	77%	937	9.10	11.08
45.04	77%	1617	8.99	10.68
45.04	77%	6400	9.37	12.45
42.71	73%	42000*	8.92	11.42
43.87	75%	12942	9.12	11.72
43.87	75%	14410	9.22	13.96
42.71	73%	26125	9.06	11.44
35.1	60%	36282	7.64	8.73
40.95	70%	36618	8.49	10.35
35.1	60%	69289	7.68	9.04
40.95	70%	69558	8.64	10.64
regression line: σ = 85.4% - 2.759% log *t* *terminated prior to rupture of specimen				
SIM creep-rupture tests				
47.97	82%	21	10.73	11.75
45.63	78%	482	9.85	12.00
43.29	74%	7699	9.57	12.81
44.46	76%	9503	9.73	12.28
41.54	71%	50360	9.34	11.77
42.12	72%	82134	9.59	12.10
40.95	70%	178168	8.94	11.85
39.79	68%	7804431	8.87	12.74
regression line: σ = 85.7% - 2.816% log *t*				

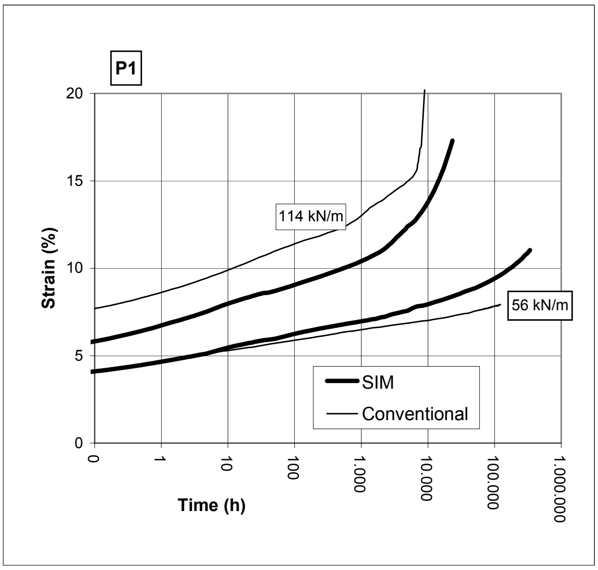

Fig. 1: Comparison between results of conventional and SIM tests on material P1. Tensile strength 206 kN/m: tests at 114 kN/m (55%) and 56 kN/m (27%).

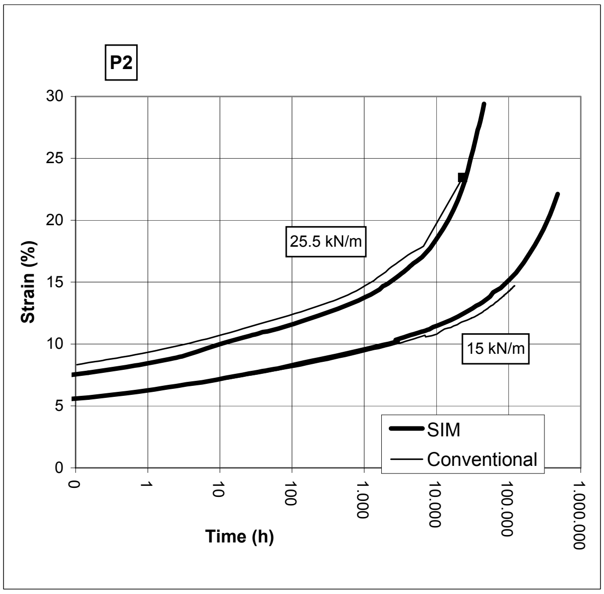

Fig. 2: Comparison between results of conventional and SIM tests for material P2. Tensile strength 49kN/m; tests at 25.5 kN/m (52%) and 15 kN/m (31%).

4 RESULTS

4.1 *Creep strain*

Figures 1 to 4 show the creep curves derived from the results of the conventional long-term creep tests and the SIM tests. The SIM tests are shown as thick lines, the conventional tests as thin lines. In this paper the criteria used for comparison are the strain after 1 h (the initial strain); the strain at the end of the conventional test (final strain); and the difference between these strains (the time-dependent strain). The total strain at any time is the sum of the initial strain and the time-dependent strain. At the risk of over-simplification, the strain developed at 1 h could be taken to be that occurring during construction, and that after 1 h as the strain generated in service.

Figure 1 shows the derived creep curves for P1. At a load of 56 kN/m (27% of tensile strength), the SIM data give a higher strain than the measured values. For example, at 122374 h the results of the conventional test give a total strain of 7.92% and a time-dependent strain of 3.21%, whilst for the equivalent time the SIM data predict strains of 9.61% and 4.95% respectively. Thus the time-dependent strain is overpredicted by 1.74% strain - or 54% as a proportion of the actual strain. At a load of 114 kN/m (55% of tensile strength), the initial strain (that is, at 1 h) recorded in the conventional test was 8.62%, whilst the SIM data predicted a value of 6.73%: this wide variability is not an unusual phenomena in creep testing. The variability can be reduced by performing additional “ramp-and-hold” tests - as indeed were used to adjust the initial strain of the conventional tests: the technique is described in 5.2 below. Nonetheless, the two creep curves are reasonably parallel until close to the rupture point of the specimen. At 7967 h, the point at which the rate of strain in the conventional test began to increase substantially, the total measured strain was 17.08%, whilst the predicted value was 13.19%. The time-dependent strains at this point were 8.46% and 6.46% respectively: thus this strain was overpredicted by 2.0% - or by 24% proportionally. The specimen in the conventional test ruptured after 9825 h at about 19% strain. The SIM test was terminated after the equivalent of 23340 h at which point the strain was 17.3%.

Figure 2 shows the creep curves for material P2. As shown there, the creep curves derived from both types of test are in good agreement. At a load of 15 kN/m (31% of tensile strength), the total strain at the end of the conventional test (121175 h) was 14.71% while the for the equivalent time the SIM data predicted a strain of 15.62%. The time-dependent strains were 8.48% and 9.36% respectively; thus the difference was 0.88% strain - or 10% proportionally. At a load of 25.5 kN/m (52% of tensile strength), in the conventional test the total strain after 6617 h was 17.90%, and for the equivalent time the SIM data predict a value of 17.13%. For the same duration, the time-dependent strains are in excellent agreement at 8.71% and 8.69% respectively. The specimen in the conventional test ruptured after 23109 h at 23% strain, and the specimen in the SIM test ruptured after the equivalent of 49000 h at 31% strain.

Figure 3 shows the creep curves for material P5 at 31 kN/m (40% of tensile strength). There is excellent agreement between the creep curves derived from the results of the conventional test and that predicted by the SIM data. The strain measured at the end of the conventional test (at 113179 h) was 10.25% and that predicted by the SIM data was 10.23%. For this time, the time-dependent strains were 4.34% and 4.85% respectively - a difference of 0.51%, or 12% proportionally.

The principal objective of the tests undertaken on material P6 was to compare the creep-rupture characteristics, and so the tests were not necessarily performed at the same load levels. However, the results of a pair of tests that were undertaken at the same load (of 40.95 kN/strip, or 70% of tensile strength) are shown in Figure 4. The data from the conventional test indicate a strain of 10.64% at the end of a test (at 69558 h) and a time-dependent strain of 2.00%. The predicted strains derived from the SIM test were 11.11% and 2.17% respectively. The high initial strain and low time-dependent strain are typical of polyester. The difference in the time-dependent strains is small at 0.17% strain - or 9% proportionally.

4.2 *Creep-rupture*

With material P1, the specimen in the conventional test, at a load equivalent to 55% of its tensile strength, ruptured after 9825 h at a strain of 19%. The SIM test was terminated after the equivalent of 23340 h without rupture, at which point the strain was 17.3%. With material P2, the specimen in the conventional test ruptured after 23109 h at 23% strain, while the specimen in the SIM test ruptured after the equivalent of 49000 h at a strain of 31%. In both cases, the SIM data predict a longer time to failure than recorded in the conventional test, but the difference is within the variability expected for such comparisons.

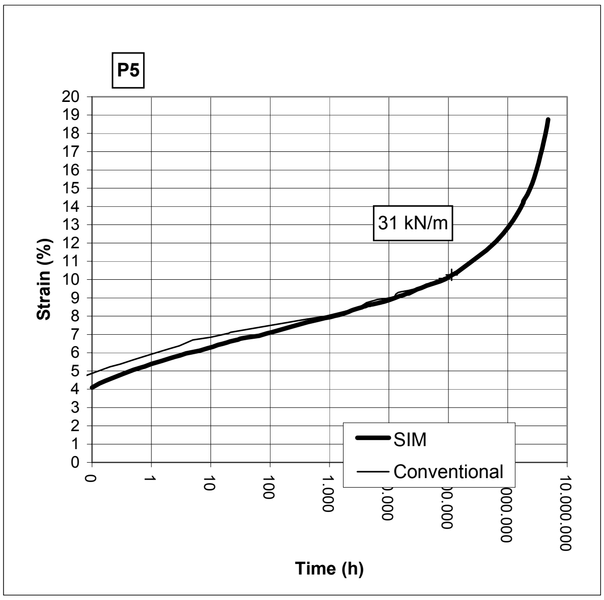

Fig 3: Results of conventional and SIM tests for polyethylene grid P5. Tensile strength 77.2 kN/m; tests at 31 kN/m (40%)

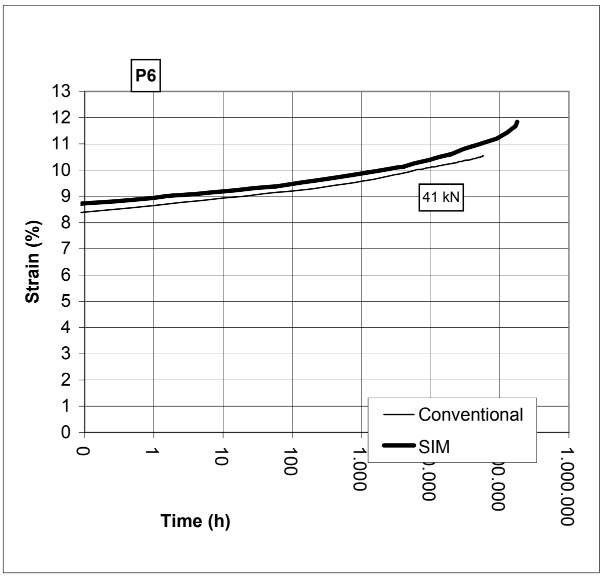

Fig 4: Results of conventional and SIM tests on polyester strip P6. Tensile strength 58.5 kN; tests at 41 kN (70%).

Figure 5 shows the creep-rupture relation for P6 derived from the results of 13 conventional creep-rupture tests and one terminated convential test, which according to convention is included since the duration of the test exceeds the prediction based on the remaining results. The relation derived from the results of the eight SIM creep-rupture tests is not shown as it is indistinguishable from that based on the conventional tests. The results of the conventional tests indicate that the design strength (as a proportion of the short-term strength) for a service life of 1,000,000 (10^6) h (114 years) should be 68.9%: the data from the SIM tests give a strength of 68.8%. It should be noted that the value of the corresponding reduction factor for creep (RF_{CR}) is 1.45.

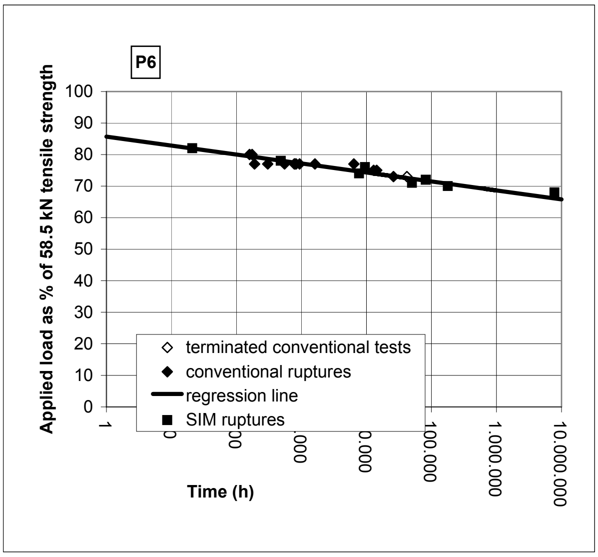

Fig. 5: Creep-rupture data for polyester strip P6. The regression line predicted from the SIM tests coincides with that of the conventional tests.

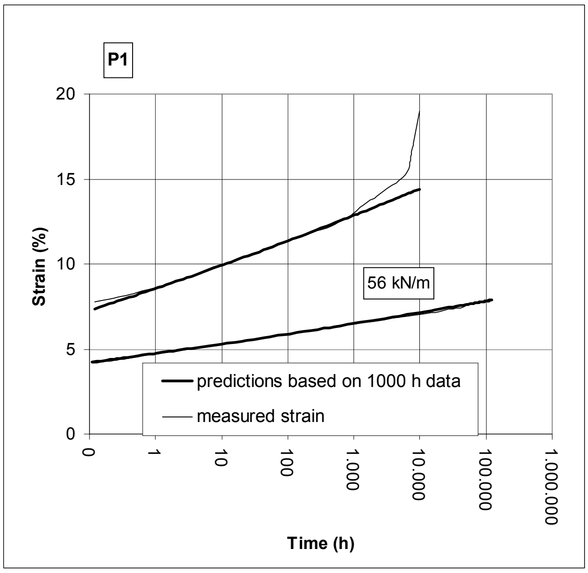

Fig. 6: Extrapolation of 1000 h data for P1

5 DISCUSSION

5.1 *Accuracy of strain prediction*

Because of the distortions of the specimen brought about by the rupture process, comparison of strains is based on the reading before rupture. A summary of the results of the conventional and SIM tests is provided in Table 2. This shows that the ratio of the predicted and measured final strains ranges from 0.77 to 1.21: the mean ratio is 1.01 and the standard deviation is 0.10. It also shows that the ratio of the predicted and measured time-dependent strain ranges from 0.76 to 1.54: the mean ratio is 1.10 and the standard deviation is about 0.21. However, it is apparent that the predictions for the heavy woven polypropylene material P1 are far less accurate than for the other materials.

Table 2 Comparison between the results from conventional creep tests and predictions based on the data from SIM tests

Material	P1	P1	P2	P2	P5	P6
Type	PP	PP	PP	PP	PE	PET
load (kN/m)	114	56	25.5	15	31	41 kN
% tensile strength	55	27	52	31	40	70
Conventional test						
duration (h)*	7967	122374	6617	121175	113179	69558
initial strain at 1 h (%)	8.62	4.71	9.19	6.23	5.92	8.64
final strain (%)	17.08	7.92	17.90	14.71	10.26	10.64
time-dependent strain (%)	8.46	3.21	8.71	8.48	4.34	2
SIM predictions						
initial strain at 1 h (%)	6.73	4.66	8.44	6.26	5.38	8.94
final strain (%)	13.19	9.61	17.13	15.62	10.23	11.11
time-dependent strain (%)	6.46	4.95	8.69	9.36	4.85	2.17
Errors in prediction (SIM minus conventional)						
final strain (%)	-3.89	1.69	-0.77	0.91	-0.03	0.47
time-dependent strain (%)	-2	1.74	-0.02	0.88	0.51	0.17
ratio of SIM prediction to measured final strain	0.77	1.21	0.96	1.06	1.00	1.04
ratio of SIM prediction to measured time-dependent strain	0.76	1.54	1.00	1.10	1.12	1.09
* where the test ended in rupture, this is the duration to the last reading but one						

Average errors	Average (all)	Average (P2, P5, P6)	Standard deviation (all)
final strain (%)	-0.27	-0.15	1.96
time-dependent strain (%)	0.21	0.39	1.25
ratio of SIM prediction to measured final strain	1.01	1.01	0.10
ratio of SIM prediction to measured time-dependent strain	1.10	1.08	0.21

The predicted strains for materials P2, P5 and P6 are reasonably close to the measured values (range 0.96 to 1.06 for final strain and 1.00 to 1.12 for time-dependent strain).

5.2 *Variability in initial strain*

As noted above, there can be quite a wide variability in the measurements of the initial strain in creep tests. In the conventional tests the creep curve was adjusted using the following procedure (Greenwood 1990):

- Perform two additional creep tests at the same load, each lasting just 1 h.
- Measure the strains after 1 h.
- Calculate the average of the strains after 1 h for the long-term test and the two additional tests.
- Subtract the strain after 1 h for the long-term creep test from this average.
- Add this difference to all strains measured for the long-term creep test.

In effect the above shifts the entire long-term creep curve such that it passes through the average strain measured after 1 h: the time-dependent strain is unchanged. This procedure has been named "ramp-and-hold" (Thornton et al 1999). The data from the SIM tests were not adjusted.

The agreement in the time-dependent strains determined by the conventional and SIM tests is no better than that between the final strains, but it would have been worse had the initial strains of the conventional tests not been corrected. This shows that better estimates of the intial and final strains can be obtained by undertaking these additional ramp-and-hold tests.

Table 3 Strains predicted from 1000 h data

Material	P1	P1	P2	P2	P5	P6
Type	PP	PP	PP	PP	PE	PET
load (kN/m)	114	56	25.5	15	31	41 kN
% tensile strength	55	27	52	31	40	70
a_0 (see Section 5.2)	8.560	4.744	9.347	6.249	5.941	8.662
a_1	1.327	0.538	1.162	0.743	1.018	0.236
a_2	0.035	0.015	0.182	0.097	-0.112	0.021
duration (conventional test) (h)*	7967	122374	6617	121175	113179	69558
final strain (%)	17.08	7.92	17.90	14.71	10.26	10.64
final strain predicted from 1000 h test (%)	14.27	7.88	16.45	12.53	8.23	10.30
error in prediction of final strain	-2.81	-0.04	-1.45	-2.18	-2.03	-0.34
ratio of 1000 h prediction to measured final strain	0.84	0.99	0.92	0.85	0.80	0.97

* where the test ended in rupture, this is the duration to the last reading but one

Average errors	Mean	Standard Deviation
error in prediction of final strain	-1.48	1.09
ratio of 1000 h prediction to measured final strain	0.90	0.08

5.3 *Predictions based on 1000 h tests*

A simple and quick alternative to SIM testing would be to extrapolate creep data obtained from 1000 h long tests - as performed by Watts et al (1998). To test the success of this approach, a quadratic relation was fitted to the strain measurements:

strain = $a_0 + a_1 \log t + a_2 (\log t)^2$

from 1 h ($\log t = 0$) to 1000 h ($\log t = 3$) and this was then extrapolated to longer times. The coefficients and results are summarised in Table 3 and an example is shown in Figure 6.

It is clear from eamination of the final strains in Table 3 that the extrapolations underestimate the final strain. The predictions are only satisfactory, i.e. within 1% strain, where the creep curves are reasonably straight; for example, for material P1 at the lower load, and for polyester P6 at a higher load. Furthermore, for material P5, the quadratic term was negative - reflecting the downward curvature between 1 and 1000 h, but at longer durations the curvature was upward. Inaccuracy would also be expected in polyesters in and around the region of the typical inflexion in the stress-strain curve.

Furthermore, an examination of the data in Figure 5 indicates that limiting creep-rupture tests to 1000 h would not be sufficient to define the gradient of the creep-rupture characteristic.

5.4 *1000 h tests as validation of SIM*

1000 hour long conventional tests do, however, serve an important purpose. Normally an approvals authority will request a number of 1000 h conventional creep tests to be undertaken as a means of validating predictions based on SIM tests. A 1000 h test will provide a measure of the initial strain and the correct slope of the creep curve over three log cycles of time.

Initially a 7ºC step was used for SIM tests on polypropylene materials P1 and P2 (with a shift factor of approx. 0.14 decades per ºC) and six steps (up to 62ºC) were necessary to cover a 100-year time range. However, it was found that two independent operators selected different values for the shift factor and both predicted the strain incorrectly. The selection of a 14ºC step eliminated this subjectivity and with guidance from the data obtained from the first 1000 h of a conventional creep test, the SIM was found to provide accurate predictions. For these materials, and others, the data from a 1000 h creep test can verify the temperature shift factors corresponding to two temperature transitions. Since the shift factors are not strongly temperature dependent, this will guide the choice of the remaining shift factors. Thus a conventional 1000 h test provides both an independent measurement of the initial strain and verification of the shift factors and is, therefore, likely to lead to a more accurate prediction.

To cover a third temperature transition, the duration of a conventional creep test would have to be extended from 1000 h (or about six weeks) to 4000 h (or about six months).

5.5 *Accuracy of rupture prediction*

The differences in the measured and predicted times to rupture for materials P1 and P2 are rather large, but at this point they are regarded as within the scatter expected of such measurements: it should be noted that the SIM data predict longer durations.

The measured and predicted creep-rupture characteristics for the sheathed polyester strip material P6 hardly differ. Thus in this case the design strengths and reduction factors RF_{CR} predicted by both methods are identical. Nevertheless it is recommended that a small number of conventional tests, typically three, should be performed to verify a creep-rupture characteristic generated using SIM. A duration of between 50 and 1000 h will verify at least two temperature steps of the SIM test.

6 CONCLUSION

For three of the four materials tested, the results of SIM tests provide reasonably accurate predictions of the strains measured in conventional creep tests. The durations used for comparison range from 8 to 14 years. Less accurate predictions are made for a heavy woven polypropylene .
Where the results of SIM tests are to be used for predictions, it is recommended that ramp-and-hold tests are used to correct the initial strain (at 1 h) and that 1000 hour long conventional creep tests are used to valid the SIM shift procedure.

The times to rupture predicted using the data from SIM tests agree excellently with those predicted by conventional testing for polyester. For polypropylene, the SIM predicts longer times to rupture, but the variation is within the expected level of variability for the limited amount of data available.

7 ACKNOWLEDGEMENTS

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