Creep and Time-to-Rupture of Polyester Geogrids at Elevated Temperatures

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ABSTRACT
As in reinforced walls the active loads will not decrease during the service life of the construction, data on creep and creep rupture of the reinforcement are of paramount importance. For the endorsement of our woven polyester geogrid in Hong Kong, measurements of the geogrid have been carried out at temperatures of 40 and 60°C, with creep loads ranging from 87.5 to 65% of the short-term strength. The investigations were accomplished in accordance with the new European (CEN) Draft Standard on Creep and Creep Rupture.
The results are presented in stress-rupture diagrams and creep curves for either temperature.
The paper discusses the accuracy of the results and presents conclusions.
Information is given on the molecular structure of polyester to explain its excellent creep and creep-rupture behaviour.

INTRODUCTION

Data on creep and creep rupture of geotextiles and geotextile-related products are important for any reinforcement application, and even of paramount importance for reinforcement of retaining walls, since in these walls the active loads will not decrease during service life of the construction. Moreover, in (sub)tropical sunny regions the temperature of the fabric or geogrid in critical zones of the construction may reach values of 40°C or higher.
For the endorsement of our woven polyester (PET) geogrid Fortrac® in Hong Kong, measurements on creep and creep rupture were therefore performed at 40°C, with additional measurements at 60°C.

2 PERFORMANCE OF CREEP TESTS

2.1 Apparatus

To create the controlled-temperature zones, with a temperature deviating from the standard surrounding 20°C, vertical glass tubes were installed with a diameter of approximately 50 mm, and a length of 1 m (see Figure 1). The glass tubes permit creep measurement by means of an optical system. Pressurized, heated air is blown into a side-tube branching off the bottom end of the vertical tube at a 45° angle. Temperature in the vertical tube is controlled by a thermocouple at the inflow, connected with the heating element through a Eurotherm multifunction temperature control unit. The specimen is suspended in the vertical tube, and is clamped at either end by large 115-mm-dia capstan grips of proven adequacy for testing a single Fortrac bundle. The mass of the lower grip (1,200 g) approximately equals the **standard pretension** of the bundle. (= 1% of the tensile strength). The lower grip can be loaded with additional dead weight to obtain the required creep load total. Rupture of the bundle arrests a digital clock.

The temperature in the vertical tube is mainly dependent on:
- the T-setpoint on Eurotherm control unit;
- the position of input control thermocouple;
- the flow rate/input pressure of heated air.

The setpoint accuracy of the digital Eurotherm is 1 °C, but temperature adjustment starts at a deviation from the setpoint of 0.2°C; the Eurotherm unit features variable overshoot control.
The highest temperature in the vertical tube is measured at the inflow of heated air from the side-tube. Upwards from there, temperature decreases gradually.
The input control thermocouple is positioned in the zone of highest temperature. Figure 1 also shows the temperature pattern over the tube for

T = 40°C.
So far, our experiments have not found any significant change in the temperature pattern over time.

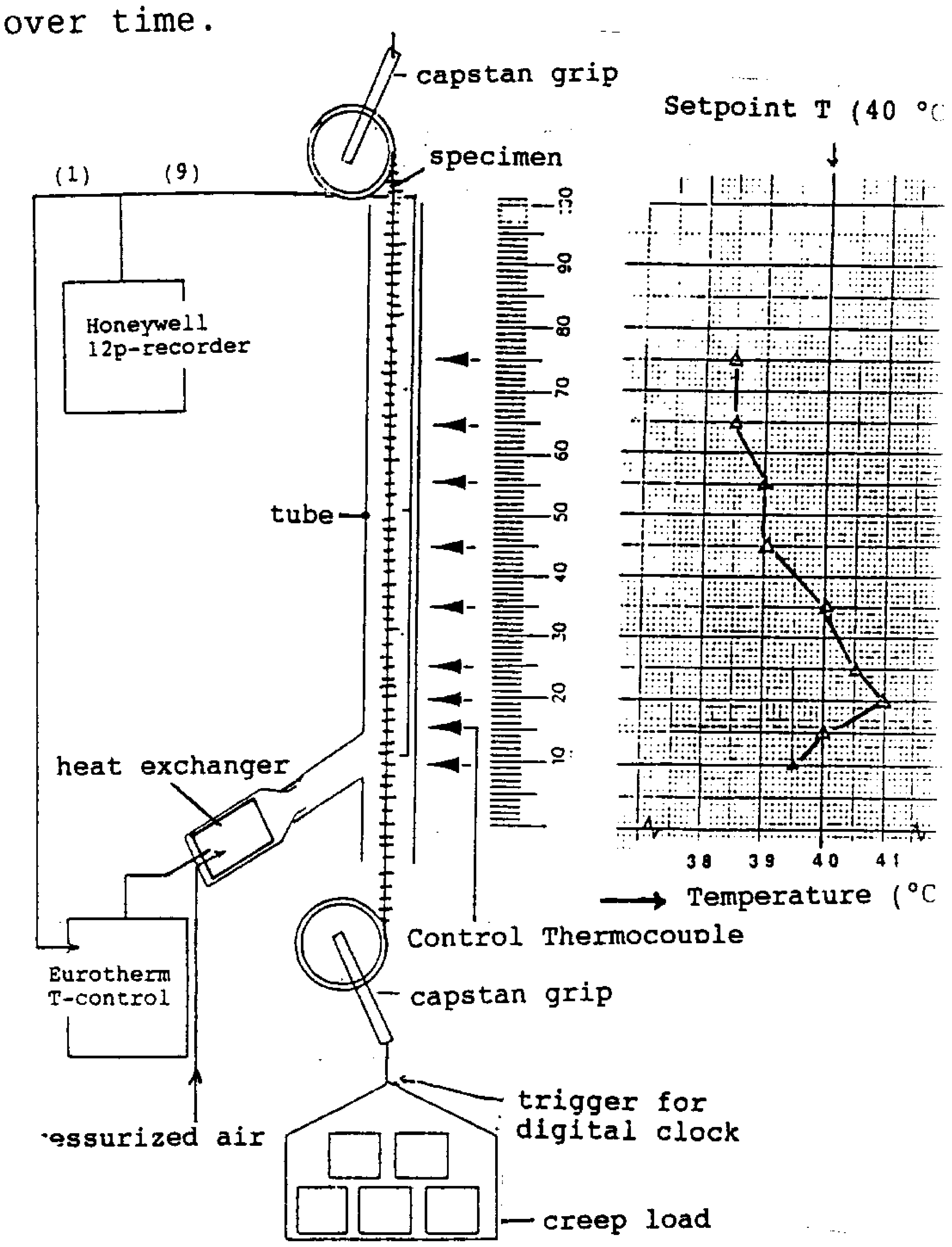

Figure 1. Diagram of apparatus and temperature distribution in the tube at setpoint T = 40°C.

The optical system used to determine changes in gauge length consists of a centrally positioned cathetometer fitted with two separate monocular telescopes. (The cathetometer serves 50 other creep positions not related to this report). The overall accuracy (adjustment + reading) is ± 0.1 mm.

2.2 Type and size of specimens

In accordance with the recent European Draft Standars on Tensile Creep (see §2.3) a specimen width was chosen so as to comprise one single tensile element: i.e., one bundle of yarns cut from an actual grid sample, including pieces of all cross-bundles, at the typical grid width of 24 mm.
The specimen length between the grips is 1.1 m, of which approx. 480 mm (under preload) is taken as the gauge length.

2.3 European Draft Standard on Tensile Creep

The main distinguishing feature of the above draft standard (Ref. 5) is that the size of the specimens is not uniformly prescribed for all different types of geotextiles or related products. Instead it is determined on the basis of specific sample properties as lateral contraction, tensile strength and tensile strain. Any laboratory that ever determined, or tried to determine, the wide-width tensile strength of really strong woven geotextiles will understand why: The Wide-width Tensile Test (WwTT) was specifically developed for nonwoven geotextiles - a class exhibiting high lateral contraction, low strength and high strain at rupture - in order to obtain tensile values better related to field conditions than those determined in a strip tensile test.
The WwTT remains useful for these light-weight nonwovens, with tensile strengths (far) under 50 kN/m.
But geoproducts however used for reinforcement, where creep behaviour is of the utmost importance, generally exhibit low, even negligible, lateral contraction, low strains, low creep, and a (very) high tensile strength: In woven geotextiles, tensile strengts up to 1000 kN/m are not uncommon, and even in (woven) geogrids a tensile value as high as 450 kN/m was recently encountered.
For creep and creep-rupture measurements the draft standard therefore allows the use of the technically representative width (TRW), being the smallest width that exhibits, up to a specified accuracy, identical tensile strength/strain characteristics per unit width as the product in the Wide-width Tensile Test .
For products with zero or negligible lateral contraction it can be proven that the TRW is one single tensile element: for geogrids one single rib or bar, provided that it is carefully removed from the geogrid sample. For the woven geogrid considered here, it has been shown that one bundle of yarns (including pieces of all cross-bundles) is representative.

It is clear that the method proposed in the draft standard has considerable advantages over other methods used (especially for low creep, high strength samples) in point of:
- reduced loads, resulting in lighter apparatus and fewer jaw problems;
- higher accuracy, because the gauge length can be substantially increased.

3 STRUCTURAL PROPERTIES OF POLYESTER

The results as presented in § 4 show how creep rupture of a polyester woven geogrid depends on loading and test temperature. In general, rupture may take place near defects and inclusions which reduce strength. But changes in the physical molecular structure may also occur in testing which may cause an overall strength reduction. For a better understanding of these latter phenomena, measurements were carried out on PET yarns after creep rupture. The physical structure of the original yarn was determined as a reference. To facilitate discussion, let us first look at the applied model of that physical

structure:
Technical PET yarns have a complex semicrystalline structure in which the molecules are arrayed along the fiber axis in crystalline and amorphous domains (Figure 2, Ref.1). Within the crystals the molecules are well ordered and highly oriented, whereas in the amorphous domains coiled chains are far less orientated.
Molecules that are part of crystals may run through several crystalline and amorphous regions (tie molecules) or may fold back to re-enter the crystal. All chains end in amorphous domains.

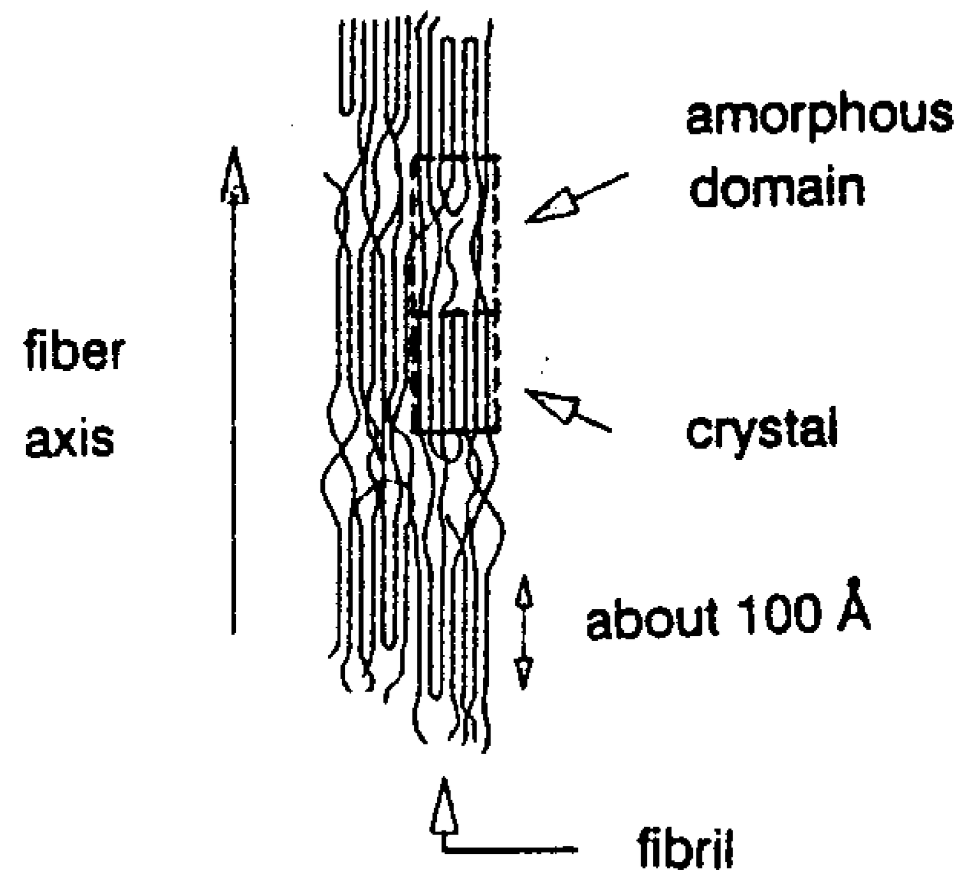

Figure 2 Two-phase model of the PET molecular structure

This molecular ordering gives rise to the formation of so-called fibrils, i.e. structural units with cohering crystalline and amorphous domains, predominantly in axial direction.
The physical structure of PET yarns can be described in greater detail, but the above two-phase model has proved very useful in characterizing yarns in terms of their crystalline morphology, amorphous orientation and molecular weight. In the present case such parameters were obtained by combining data on the overall density (D), X-ray diffraction patterns, birefringence, Differential Scanning Calorimetry (DSC) and Size Exclusion Chromatography (SEC).
For details, see Refs. 1 - 3.
From these data the following physical structure parameters were calculated:

LAM.100 (Å)	Average crystal thickness perpendicular to the b-axis of the unit cell.
LAM.010 (Å)	Average crystal thickness perpendicular to the a-axis of the unit cell.
LAM.-105 (Å)	Average crystal height.
Sc (10^{-5} Å^3)	Average crystal size.
Dc (kg/m^3)	Average density of the crystals.
Vc	Crystalline volume fraction.
Fa	Average amorphous orientation.
Tm (°C)	Melting point as determined with DSC
Mn	The number average molecular weight as determined with SEC.
Mw	The weight average molecular weight.
Mz	Fraction with the highest molecular weight.
Mw/Mn	The polydispersity: A measure for the width of the molecular weight distribution.

4 RESULTS

The results are presented in three separate sections, concerned with, successively, the creep-rupture tests at 40 and 60°C, the creep tests at 40 and 60°C, and structure-physical investigations of PET yarns before and after creep loading up to 3 years.

4.1 Creep-rupture at 40 and 60°C

The times-to-rupture of one warp bundle of Fortrac 55/30-20 are presented numerically in Table 1 and graphically in Figure 3.
For both temperatures, the load % is related to the tensile strength at 20 °C (1.388 kN).
For comparison, the 60°C diagram of Figure 3 also shows the stress-rupture line at 20°C.

Figure 3 Stress-rupture lines at 40 and 60°C. The solid lines are regression lines of the measured times-to-rupture. The top dashed lines represent 95 % confidence limits, the bottom dashed lines are 95 % **lower boundary prediction lines for one bundle.** The broken line at top right represents the stress-rupture line at 20°C as reported previously (see Ref. 4).

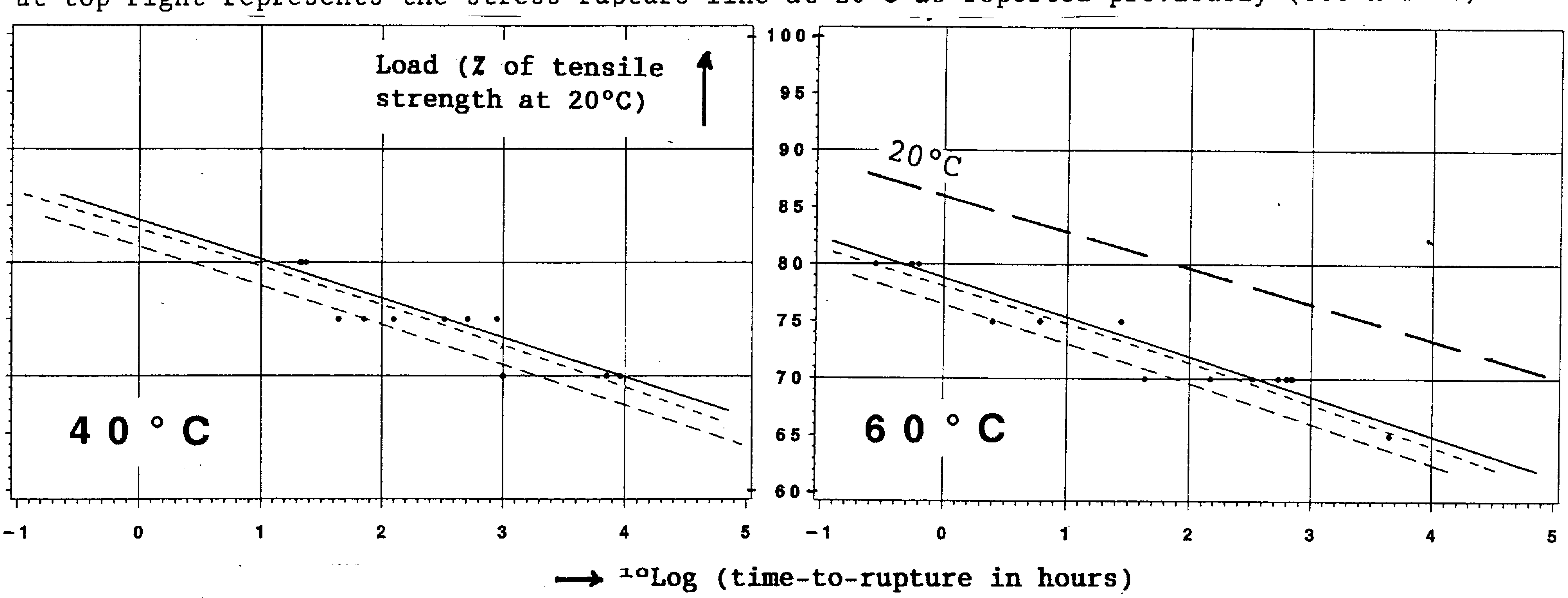

Table 1 Time-to-rupture in hours of one Fortrac® bundle, at 2 temperatures and various load % (related to strength at 20°C).

load %	87.5	80	75	70	65
40°C	0.2	22.2	71.6	1003	
	0.8	21.1	43.9	> 9142	
		23.9	126	7101	
			516		
			332		
			893		
60°C		0.3	6.1	149	> 4461
		0.5	2.5	330	> 4462
		0.6	27.7	43.3	> 4463
				631	> 4465
				530	
				710	
				680	

As there was some uncertainty about the exact magnitude of the load percentage presented as 87.5 %, the corresponding values for time-to-rupture were omitted from Figure 3 and from the regression analysis.

4.2 Creep at 40 and 60°C

Some representative creep curves at various loading percentages are shown in Figure 4 and Figure 5 (40°C and 60°C respectively).

4.3 Structure analysis

The results of the structure analysis are summarized in Table 2 (data on crystal structure) and Table 3 (data on orientation and molecular weight distribution).

Specimens 1 - 4 were obtained from yarns after 3 years of creep testing at 20°C under 50 and 60% load. Specimen 5 represents the control yarn.

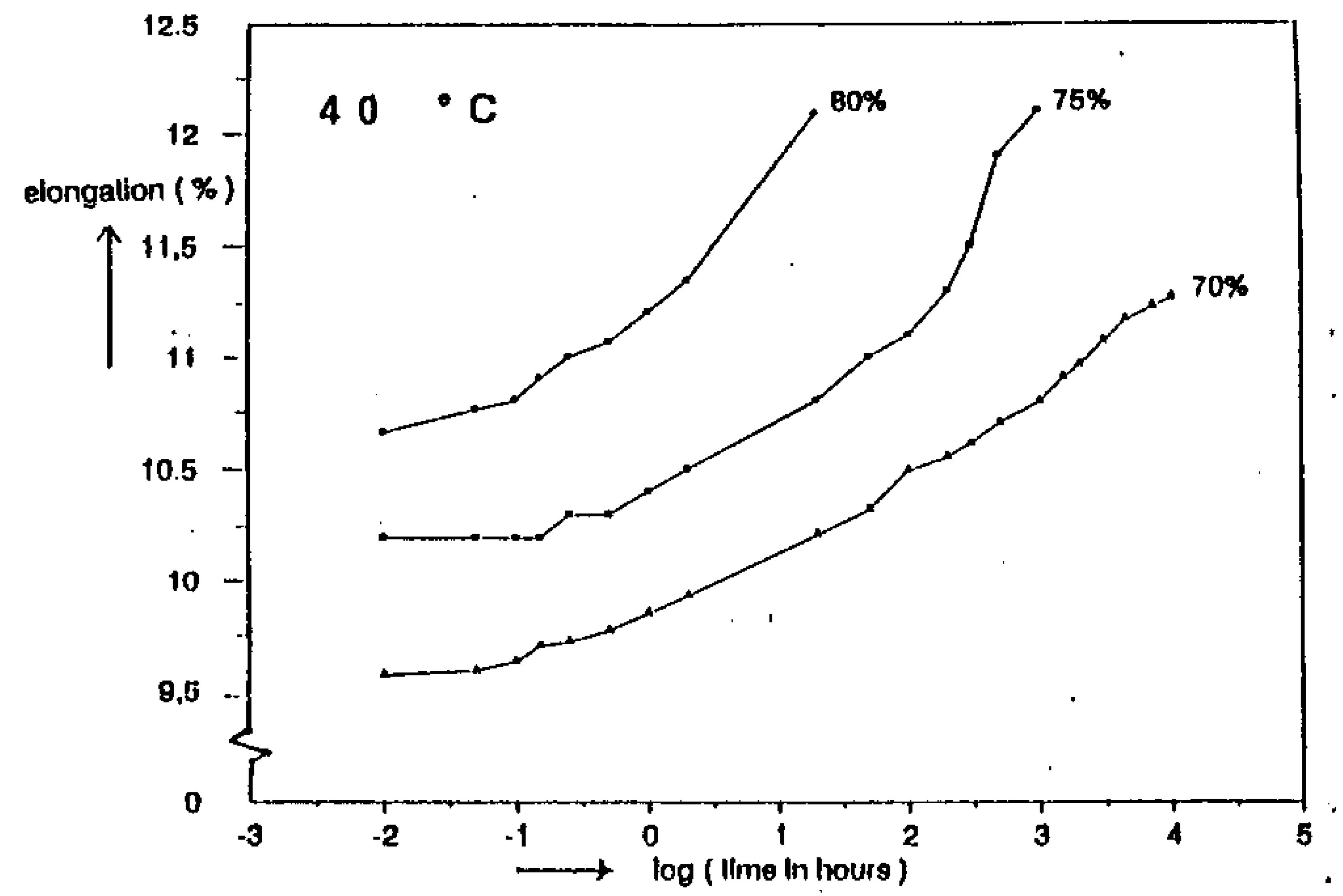

Figure 4 Representative creep curves at 40°C

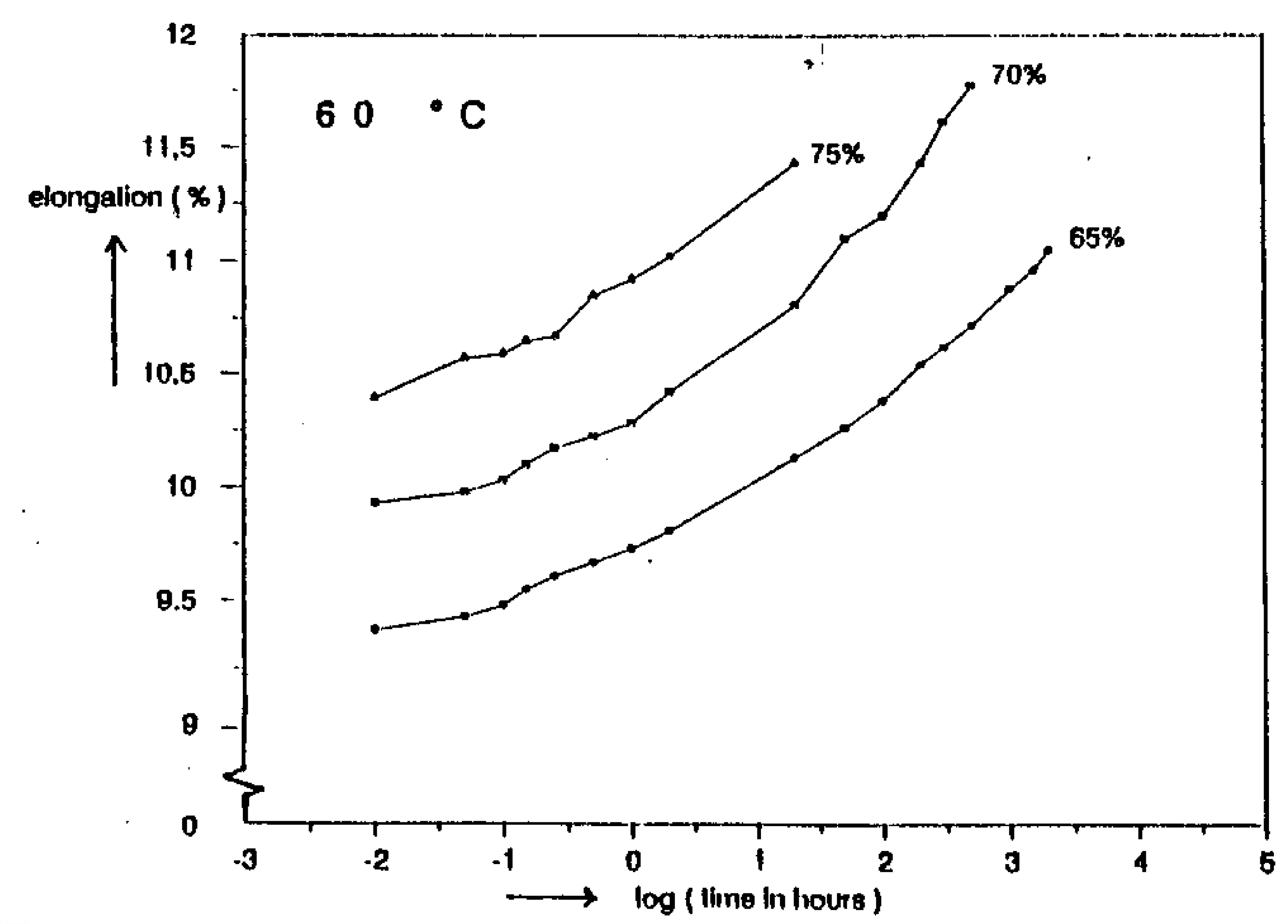

Figure 5 Representative creep curves at 60°C

Table 2 Data on crystal structure of PET yarns, **after** 3 years of creep loading **(Specimens 1 - 4)**. Specimen 5 is the **unloaded control** yarn.

Spec. No.	LAM. 100 (Å)	LAM. 010 (Å)	LAM. -105 (Å)	a-axis (Å)	crystal size Sc (Å³ * 10⁻⁵)	coarseness Sa (Å³ * 10⁻⁵)	crystal density Dc (kg/m³)	overall density D (kg/m³)	cryst. volume ratio Vc	DSC melt peaks T1 (°C)	DSC melt peaks T2 (°C)
1	49	78	97	4.461	3.6	5.6	1501	1405.3	0.393	246	253
2	51	77	96	4.477	3.8	6.2	1503	1403.9	0.379	245	254
3	51	77	95	4.480	3.8	6.4	1503	1402.6	0.371	248	256
4	48	75	100	4.476	3.6	6.2	1504	1402.7	0.371	247	255
5	52	80	101	4.486	4.2	7.3	1500	1401.1	0.367	247	257

Note: 1 Å = 10^{-10} m

Table 3 Data on amorphous orientation and molecular weight. PET yarns identical to Table 2.

Spec. No.	filament diameter (µm)	birefringence	amorph. orient. Fab	molecular weight distribution Mn	Mw	Mz	Mw/Mn
1	22.7	0.1869	0.607	13400	34100	59000	2.55
2	22.0	0.1898	0.628	13700	34300	58000	2.49
3	22.2	0.1897	0.630	13500	33900	58000	2.50
4	22.0	0.1888	0.625	13400	34000	59000	2.54
5	22.3	0.1894	0.628	13600	34100	58000	2.51

5 DISCUSSION

- The impact of temperature fluctuation is not exactly the same for the creep and creep-rupture measurements: It was observed that specimens nearly always rupture in the narrow zone near the inflow of heated air, hence temperatures of (40 ± 1)°C and (60 ± 1)°C are considered as being correct for creep-rupture.
For the creep values, however, the temperature over the entire gauge length of 480 mm should be taken into account, i.e. (40 ± 2)°C and (58 ± 3)°C respectively.

- The very high precision of the optical system ensures that creep measurements are quite accurate. Related to the gauge length of approx. 480 mm, the total measuring inaccuracy of ± 0.2 mm corresponds with an error of ± 0.05%.
However, related to the initial strain level of roughly 10%, this length inaccuracy means a relative strain error of ± 0.5%. Or even, when related to a mean creep value of 2% abs. in one year under the conditions given, a relative creep error of ± 2.5% ! These figures illustrate that for high modulus low creep polymers the choice of a long gauge length is vital to obtain a good accuracy. For a WwTT specimen with a gauge length of 60 mm and the same measuring inaccuracy of ± 0.1 mm, creep readings would be accurate within limits of ± 20% only!

- From Figure 3 it is clear that the stress-rupture line at 40°C is not too different in position and gradient from that for 20°C.
The short-term tensile properties of polyester were already known to be largely unaffected by a temperature increase to 40°C, but for the long-term properties ($P_{char.}$ at 120 years) a reduction of 4 % has been demonstrated now.
The further downward shift of the stress-rupture line at 60°C can be explained for the major part by the recognized drop in short term tensile strength of approximately 5%.
Extrapolation of the data measured produces the characteristic strength diagram presented in Figure 6.

- In looking at Figure 3 it should be borne in mind that for design purposes the 95% prediction line is valid for time-to-rupture of **one** single bundle of the geogrid.
But in field conditions with more than 100 bundles acting together in wide grids, it is likely that the 95% prediction line will coincide with the regression line.
In that case the 95% lower confidence limit applies to the absolute minimum time-to-rupture.

- The creep plots (Figures 4 and 5) show the upward curved contour that even polyester exhibits at high loading percentages. For 40°C, at least, it is plain that the curve is flatter

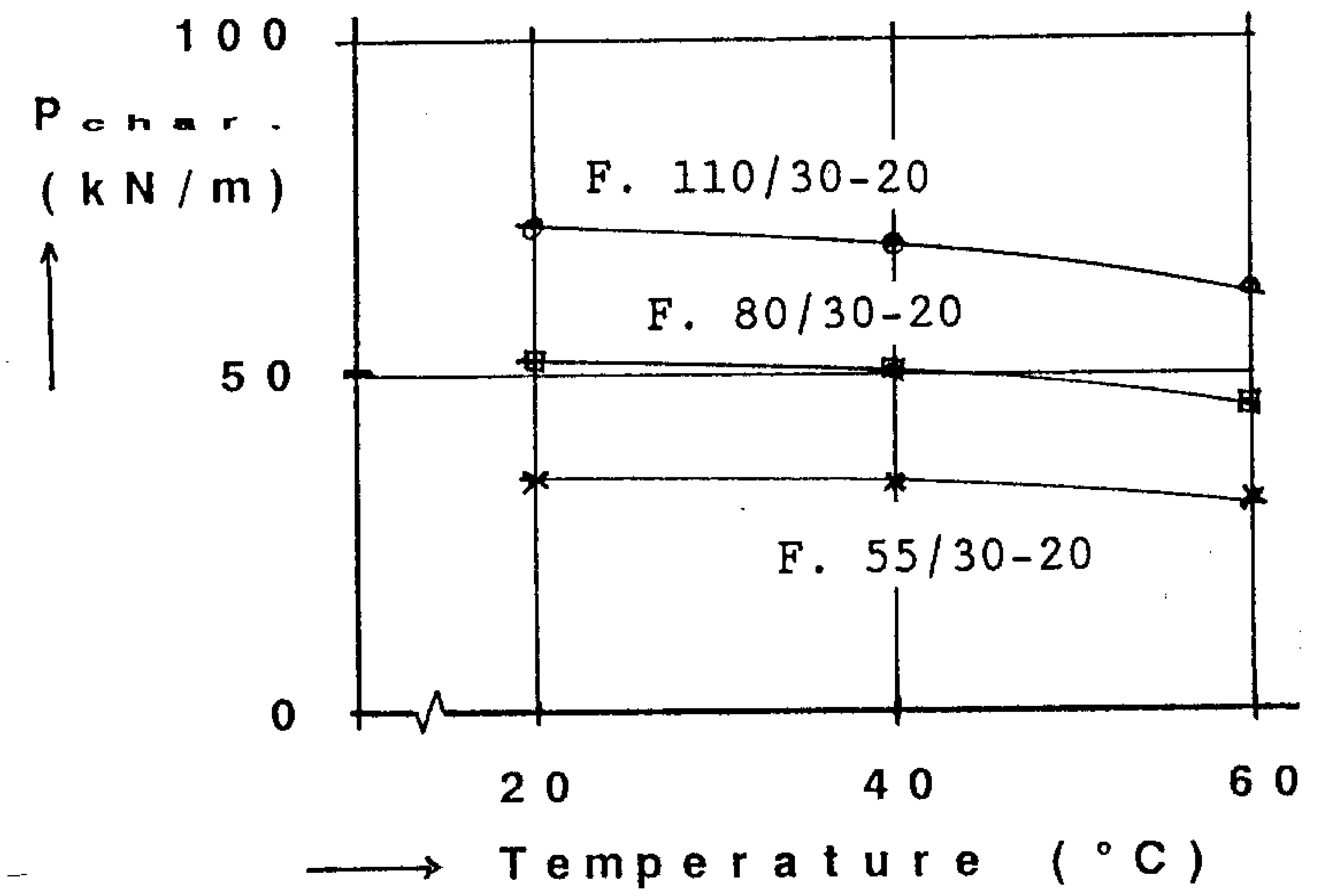

Figure 6 Temperature dependence of the characteristic strength (120 years) of Fortrac® geogrids.

and straighter at lower loads. Creep measurements for more realistic creep loads of (say) 30 - 40% at 40 and 60°C are planned for the future; the times-to-rupture, however, should be too long for our lifetime.

- Tables 2 and 3 reveal that creep testing of the PET yarns does **not induce large permanent changes** in physical structure.
This is no doubt attributable to the presence of crystals in which strong dipole-dipole and π - π interactions hinder the slipping of tie molecules.
In a material such as polyethylene (PE) there are only weak Van der Waals interactions and consequently molecular slipping is much easier.
A more detailed examination of the results permits the conclusion that some **small** permanent changes in structure have taken place during testing. First of all the size of the crystals has slightly reduced and their density (Dc) and quantity (Vc) has increased somewhat. This suggests a small permanent reorganisation of the crystalline structure during creep testing, resulting in smaller but more - and more densely packed - crystals.
The stability of the physical structure is also expressed in the constancy of the molecular weight distribution of the tested yarns (Table 3). Only near the edges of a break, a small drop in Mz by about 5% is observed (data not presented here). These results support the idea that the ultimate yarn rupture is a local event initiated by defects under stress (see also Ref. 1).

- The yarns analyzed after 3 years of creep loading, had been loaded to 50 - 60% of their tensile strength, i.e. near their second modulus peak (see Figure 7), marking the point where molecular **overstretching** starts and taut tie molecules may break (see Ref. 1).

The times-to-rupture presented in Table 1 and Figure 3, however, were for specimens loaded to 65 - 87.5% of their tensile strength. So these specimens were overstretched right from the start. In most applications,loading will be less, and overstretching will be absent, Linear extrapolation of the stress-rupture lines presented is therefore quite likely to be conservative, and under conditions that are comparable in all other aspects longer times-to-rupture can be expected.

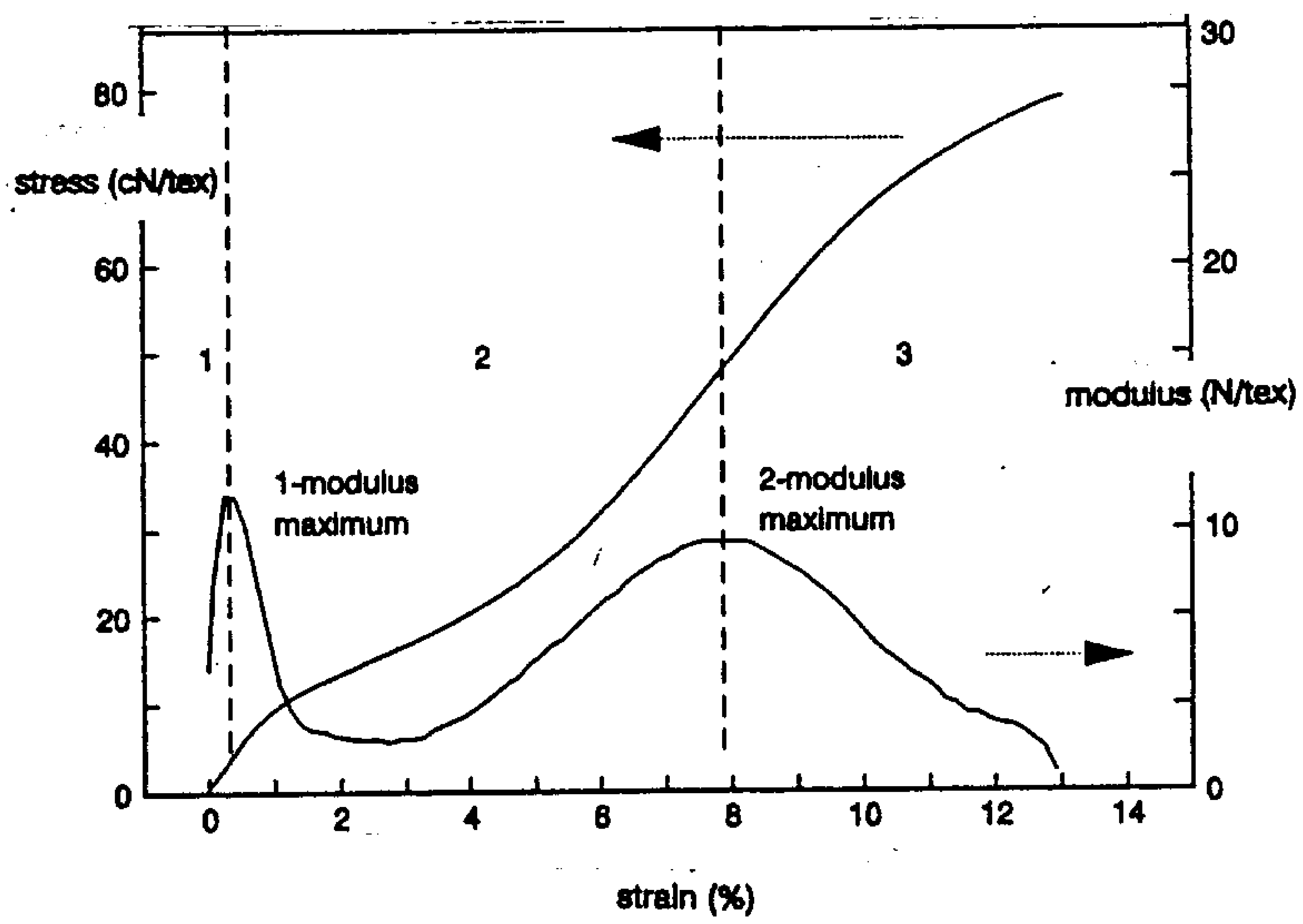

Figure 7 Stress-strain and modulus-strain curves of a PET yarn, indicating 3 separate regions:
(1) breakdown of the amorphous entanglement network,
(2) molecular uncoiling by "gauche" - "trans" transitions, and
(3) local rupture of taut tie molecules.

6 CONCLUSIONS

- Up to a temperature of 40°C the long-term creep and creep-rupture properties of Fortrac® woven polyester geogrids are only slightly affected by temperature.
At 40°C the stress-rupture line was found to be shifted downward, resulting in a 4% reduction compared to 20°C in characteristic strength for a 120-years design life.

- At a temperature of 60 °C a significant drop in tensile strength can be recognized, resulting in an 8 - 10% downward shift of the stress-rupture line compared to 20 °C.

- Although no long-term measurements were carried out at temperatures over 60°C, it can be safely said that polyester should not be used for long-term reinforcement at temperatures over the glass transition temperature of approximately 65°C.

- For creep and creep-rupture measurements it can be concluded, based on our experiments and experience with high-strength, high-modulus woven geotextiles and geogrids, that replacement of the Wide Width by the Technically Representative Width - as proposed in the European draft standard - would save much time and money.

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