



National Physical Laboratory

Good Practice Guide No. 2

Measurement and Analysis of Creep in Plastics



TECHNICAL LEVEL

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Foreword

This guide describes procedures for obtaining creep data from plastics testpieces as a function of age at different temperatures and at low stresses which have been developed by the National Physical Laboratory. In describing the measurement procedures this guide is intended to complement the ISO standard concerned with the determination of creep for plastics (ISO 899-1) [1]. In particular the guide contains practical advice on how to measure creep taking into account the influence of physical ageing.

The analytical procedures described in the guide are confined to a single model which may not be the most appropriate for describing the creep of all types of plastic, including amorphous, semicrystalline, fibre or particle filled, over all temperature ranges. However, the model by including the effects of physical ageing on creep behaviour, has a sound physical basis and is one of the most straightforward to use at the present time.

In the drafting of this guide, it has been assumed that the collection and analysis of creep data will be carried out by suitably qualified and experienced personnel. To ensure that the data analysis is successful, the creep measurements need to be repeatable to within 2% using the same testpiece and test conditions. We recommend the use of accurately machined testpieces and the use of calibrated equipment and stable temperature controlled environments ($\pm 0.5^\circ\text{C}$) to ensure repeatability. Precautions should also be taken to ensure that the material is structurally stable, for example, bulk adhesive specimens should be fully cured prior to testing. It should be noted that compliance with these recommendations does not guarantee the accuracy of the data which may be less than ideal due to material variability.

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Chapter 1: Scope

1. Scope

- 1 This guide gives practical advice on how to obtain tensile creep data as a function of age for plastics at low stresses and at different temperatures.
- 2 This guide describes procedures for analysing creep data to obtain parameters required by a function which can model the creep behaviour of testpieces of different ages and at different temperatures. This function may thus be used to predict the creep behaviour for times beyond that at which measurements have been made.
- 3 This guide applies to the testing of standard dumbbell or parallel sided testpieces of thermoplastics including amorphous and semicrystalline materials. The procedures also apply to thermosetting materials such as epoxies [2].

Chapter 2: Introduction

2. Introduction

Physical ageing is defined as the process of progressive densification of a glassy material which occurs with time due to conformational changes of the polymer chains. The driving force for these changes arises from the non-equilibrium chain conformations which occur when the material is quenched from a high temperature to a low temperature (see Section 6 for details). Physical ageing unlike chemical ageing is a reversible process i.e. a material aged for a number of years can be rejuvenated by a short period of annealing at an appropriate elevated temperature.

The influence of physical ageing on the creep behaviour of a plastic is shown in Figure 1 which shows a series of creep tests obtained from the same testpiece subjected to the same tensile load at different elapsed times. The elapsed time, t_e corresponds to the period of time between quenching the material from an elevated temperature to a lower test temperature and the instant of load application and serves to characterise the age of the material. The data shown in figure 1 were obtained from tests where the creep time is limited such that the age of the sample is effectively the same at the end of the test as it was at the start. This type of test is referred to as short-term and is covered by the guide in Section 8.

The short-term creep data for a testpiece of a given age can be described as shown in Figure 1 by [3]

$$D(t) = D_0 \cdot \exp\left(t/t_0\right)^m \quad (1)$$

where D_0 is the limiting compliance at short times, t_0 refers to a mean retardation time for the creep relaxation process and m characterises the width of the retardation region along the time axis as shown schematically in Figure 2.

The mean retardation time increases with increasing age of the testpiece according

$$t_0 = At_e^\mu \quad (2)$$

where A and μ are constants [3]. In contrast, the short time limiting compliance D_0 tends to decrease as the age of the sample increases which is described by

$$D_0 = Wt_e^{-\nu} \quad (3)$$

where W and ν are constant [2]. The change in D_0 with elapsed time is very much less than that observed for t_0 . Indeed for some materials D_0 can be assumed to be constant when the parameter ν is vanishingly small.

Whilst these equations can be used to model the short-term creep behaviour of materials, in practice plastics components will normally be subjected to loads for long periods of time, i.e. for times in excess of the short-term limit. This further ageing of a testpiece under load is seen

in a long-term creep test as a gradual reduction in the rate at which it creeps as shown in Figure 3. Details of how to conduct long-term creep tests are to be found in Section 9.

Mathematically, long-term creep is described by [2]

$$D(t) = W t_e^{-v} \exp \left[\int_0^t \frac{du}{(A^2 t_e^{2\mu} + C^2 u^{2\mu'})^{0.5}} \right]^m \quad (4)$$

where it can be seen that some of the parameters correspond to those obtained from short-term data. u is a dummy time variable and the parameters C and μ' in the integral allow for the progressive increase in t_0 which occurs as the testpiece continues to age during the test.

Equation (4) can only be used to predict the creep behaviour of materials at constant temperature, however this limitation can be overcome by deriving the temperature dependence of W , A and C based on their determination at several points over the desired temperature range. Details of the procedures that need to be followed are given in Section 10.

Chapter 3: Definitions

3. Definitions

For the purposes of this guide the following definitions apply.

3.1 Creep compliance, $D(t)(GPa^{-1})$

The tensile creep compliance is given by the ratio of the time dependent strain to the constant applied stress.

3.2 Elapsed time, $t_e(s)$

The period of time between quenching a specimen from the de-ageing temperature to the test temperature and the instant of load application. This is the age of the material at the start of a creep test.

3.3 Extensometer

A device used for measuring the extension of a gauge length of a testpiece in response to an applied load. The extensometer can be a strain gauge, linear variable differential transformer or similar which is used to define the original gauge length.

3.4 Limit of proportionality

The greatest tensile strain which a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooke's Law).

3.5 Long-term creep tests

Creep tests where the period of measurement is sufficiently long that the age of the testpiece at the end of the test is significantly greater than it was at the start of the test. This is taken to be any test of duration greater than $0.3t_e$.

3.6 Non-linear stresses

Stresses which result in strains which exceed the limit of proportionality i.e Hooke's Law is not obeyed.

3.7 Physical ageing

This refers to the process of ageing which involves a progressive densification of glassy materials and occurs as a result of conformational changes of the polymer chains. The driving force for these changes arises from the non-equilibrium chain conformations which occur when a material is cooled from a high temperature to a low temperature (see Section 6 for details).

3.8 Physical de-ageing

The procedure of annealing testpieces at temperatures slightly above the glass transition temperature for amorphous materials or below the pre-conditioning

temperature for semicrystalline materials which erases any structure established by the previous thermal history.

3.9 **Pre-conditioning**

This only applies to semicrystalline polymers and refers to a period of annealing at a temperature below the crystalline melting point but above that required to de-age the material which thereby ensures that the crystal content of the material remains constant with time (Section 6). Stabilization of the material's crystallinity is important to ensure repeatability of measurements on testpieces that have been subjected to a number of thermal de-ageing cycles followed by periods of ageing.

3.10 **Short-term creep tests**

Creep tests of sufficiently short duration that the age of the testpiece can be considered as being effectively constant. This period is taken to be $\leq 0.3t_e$.

3.11 **Tensile creep strain, $\varepsilon(t)$**

The tensile creep strain is a dimensionless quantity given by $\varepsilon(t) = \frac{\Delta l(t)}{l}$ where $\Delta l(t)$ is the change in length measured at time t and l is a gauge length.

3.12 **Tensile stress, σ (Pa)**

The tensile stress is defined as the force per unit area of the testpiece

i.e. $\sigma = \frac{\text{Force (N)}}{\text{Area (m}^2\text{)}}$. The cross-sectional area is a mean value determined from dimensions measured at several points in the region spanned by the gauge length.

Chapter 4: Symbols

4. Symbols

The symbols used in this guide and their significance and units are as follows:

Symbol	Significance and Units
A	Value of t_0 at an elapsed time of 1s (s)
C	The value of t_0 at a creep time of 1s (s)
$D(t)$	Time dependent tensile compliance (GPa ⁻¹)
D_0	Limiting compliance at short times (GPa ⁻¹)
$\epsilon(t)$	Time dependent tensile creep strain
$Ext_1(t), Ext_2(t)$	Measured extension of a testpiece at time t according to extensoimeters 1 and 2 (μm)
GL	Gauge length of extensometers (μm)
$LVDT$	Linear variable differential transformer
m	A parameter characterising the width of the retardation time spectrum
μ	The rate of change of the mean retardation time t_0 with respect to elapsed time is given by $\frac{d \log t_0}{d \log t_e}$ for $t \leq 0.3t_e$
μ'	The rate of change of the mean retardation time t_0 with creep time is given by $\frac{d \log t_0}{d \log t_e}$ for $t \gg t_e$
ν	The rate of change of D_0 with elapsed time given by $\frac{dD_0}{dt_e}$
σ	Tensile stress (Pa)
t	Time (s)
T	Temperature
t_e	Elapsed time (s)
T_g	Glass transition temperature (°C)
T_m	Crystalline melting point (°C)
T_0	Mean retardation time (s)
W	The value of D_0 at an elapsed time of 1s (GPa ⁻¹)

Chapter 5: Apparatus

- Testing machines
- Measurement of strain

5. Apparatus

5.1 Testing machines

Figure 4 shows a schematic diagram of a typical tensile creep testing rig with an over slung lever designed for use with plastics. In designing or purchasing such apparatus there are a number of points which should be taken into consideration in order to ensure that the data obtained is both accurate and repeatable.

5.1.1 *Rig stiffness*

The design of the creep rig should be such that there is no deformation of the frame when subjected to high loads i.e. 2 kN.

5.1.2 *Lever ratio*

The construction of the link between the lever arm and load pan and the lever arm and testpiece should be designed so that the lever ratio is independent of the position of the arm. This can be achieved by using chain links which follow arced guides on the lever arm [4].

5.1.3 *Friction*

Possible sources of friction which can give rise to stick-slip behaviour in the measurement of extension are to be found in

- the lever arm bearings - circular bearings can become 'stiff' with time
- the load train located above the specimen where friction effects can be traced to bearings and/or guides. It is recommended that load train guides are only used to mount the testpiece and are removed during the test.
- the extensometers used to measure displacement - see Section 5.2.3.

5.1.4 *Vibration*

It is recommended that the creep apparatus be mounted on anti-vibration mounts to avoid the effects of shock on the transducer output.

5.2 Measurement of strain

In general, strain measurement devices which only measure the time dependent extension on one side of a testpiece are less suitable for determining strain than those which measure it on both sides. This is particularly important if the testpiece is slightly bent when mounted where averaging the output of two extensometers will give a more accurate estimate of the creep than the output of one.

5.2.1 Accuracy

The accuracy required depends on the absolute level of strain and the rate at which it changes with time. For example, when measurements are made at high stresses or at elevated temperatures where the material is creeping rapidly, an accuracy of $\pm 1 \mu\text{m}$ is sufficient. However, for the low absolute strain levels and strain rates encountered at small stresses or during the initial period of creep tests the accuracy generally needs to be better than $\pm 0.25 \mu\text{m}$.

5.2.2 Strain gauges

Care should be taken to ensure that measurements of strain derived from strain gauges mounted on the testpiece are reliable as strain gauges tend to locally stiffen polymers such that the strain recorded is less than that expected for a given load [5].

5.2.3 Linear variable differential transformer devices

Linear variable differential transformer (LVDT) devices can be used as accurate extensometers by the addition of knife-edges as shown in Figure 5. However, there is a potential source of friction in this type of extensometer which arises from the movement of the core within the barrel which is normally designed to have limited rotational freedom. This friction can be significant giving rise to a 'stick-slip' rise in strain with time if these devices are used as extensometers on samples that have some degree of twist along their length. This can be overcome by removing the anti-rotation pins located in the barrel of the transducer.

5.3 Experimental considerations

5.3.1 Determination of the limit of proportionality

The stress at which the limit of proportionality is reached can be approximately found by applying a series of increasing loads corresponding to stresses of 1, 2, 3, 4 MPa etc to a given testpiece for short periods of time followed by extended periods of recovery e.g.

- Apply the load to the testpiece for 100 s. Remove the load and allow the testpiece to recover for at least 5 minutes.
- Follow the above procedure using an increased load.
- Calculate the time dependent compliances as described in Section 7.
- Plot compliance versus time for each set of measurements. It will become apparent when the limit of proportionality has been exceeded as the creep curves will no longer superimpose on each other.

In making these measurements it is important to use a testpiece that is at least 24 hours old to avoid any significant changes in the age of the material during the test period.

5.3.2 *Extension-measurement schedule*

To facilitate the data analysis it is advisable to use an automated data collection system which ideally collects data from the extensometers at times, which are equally spaced at 10 points per decade of log time. For tests of long duration i.e. periods of weeks or months we recommend that measurements should be made 2-3 times per day which results in more than 10 points per decade of time. This protocol ensures that any changes in the test conditions e.g. unplanned temperature fluctuations become apparent in the data. The data collection system should also be programmed to set the creep time to zero at the instant of load application. This is most easily achieved by setting a trigger voltage level for the extensometers which is below the initial strain and when exceeded on load application initiates the process of data collection.

5.3.3 *Application of loads*

It is important to apply the load to the testing machine quickly and smoothly i.e. the testpiece should be subjected to the full load within 1-2s. 'Slow' loading of the testpiece will result in data which is inconsistent with the rest of the creep curve as shown in Figure 6 while 'dropping' the weights onto the load pan will result in 'noisy' data during the first few seconds of the test.

Chapter 6: Sample conditioning

- De-ageing and pre-conditioning
- Treatment of humidity sensitive polymers

6. Sample conditioning

6.1 De-ageing and pre-conditioning

6.1.1 *Amorphous polymers*

Testpieces of unknown thermal history are de-aged by heating them to a temperature of approximately $T_g + 5\text{ °C}$ for a period of 30 minutes after which they should be quenched into water at the same temperature at which test data are required. After a period to reach thermal equilibrium of 3-5 minutes, the testpieces should be removed from the water bath, dried and stored at the test temperature in a temperature-controlled environment. This procedure can also be used to 'recycle' testpieces that have previously been tested, providing that they are not permanently deformed as a result of yielding at high temperatures.

6.1.2 *Semicrystalline polymers*

Semicrystalline polymers should be preconditioned before testing by annealing for a period of 4 hours at a temperature which is at least 20 °C above that required to de-age the material in order to stabilize the crystallinity with respect to any further temperature cycling as discussed below. After the period of annealing the testpieces should be slowly cooled to room temperature. In practice this can be achieved by simply switching the environmental chamber off and allowing it to cool.

The temperature required to deage the material should be approximately + 5 °C higher than that of the highest temperature relaxation process observed by dynamic mechanical thermal analysis at a frequency of 1 Hz.

6.2 Treatment of humidity sensitive polymers

Whilst humidity sensitive materials need to be stored in controlled environments to ensure comparable moisture content of different testpieces it is still advisable to quench the material into water after the annealing period and not into air. This action assumes that there will be negligible uptake of water by the material during the quenching period and more importantly ensures that the results of creep tests are repeatable. Reliance on air cooling can result in cooling rates that are not accurately repeatable.

Chapter 7: Calculation of compliances

7. Calculation of compliances

- 7.1 The dimensions of the testpiece are determined by making at least 5 measurements of width and thickness over the region covered by the extensometers. These results are then averaged and subsequently used in step 3 to calculate the mean stress.
- 7.2 Convert the measured extensions at each time to strains and then determine the average strain using

$$\varepsilon(t) = \frac{\frac{Ext_1(t)}{GL} + \frac{Ext_2(t)}{GL}}{2} \quad (5)$$

- 7.3 Calculate the tensile stress using

$$\sigma = \frac{Load(N)}{Area(m^2)} \quad (6)$$

- 7.4 The creep compliance at time t is then given by $D(t) = \frac{\varepsilon(t)}{\sigma}$ (Pa^{-1}). For convenience multiply the creep compliance by 10^9 so the units become GPa^{-1} .
- 7.5 Plot graphs of compliance versus time for each set of data on the same set of axes as shown for example in Figure 6. Check the data for erroneous points as illustrated in Figure 6, these are particularly likely to occur during the first few seconds of the test as a result of the load being applied too slowly. If erroneous points are located then they should be removed so that they do not influence the parameters obtained from the fitting procedures.

Chapter 8: Procedure A

- Experimental programme
- Analysis of creep data

8. Procedure A: Determination of short-term creep parameters at low stresses

Parameters that serve to characterise creep curves i.e. their shape (m), location along the time axis (t_0) and limiting compliance at short times (D_0) it is a function of the age of a testpiece over a limited time span at constant temperature can be obtained from a series of short-term tests.

8.1 Experimental programme

- 8.1.1 The testpiece is de-aged to remove any previous thermal history effects by annealing at an elevated temperature, following the procedure described in Section 6 for a period of 30 minutes.
- 8.1.2 Quench the testpiece into a water bath maintained at the temperature at which the test is to be conducted for a period of 3-5 minutes. Note the time at which the material is quenched, this corresponds to zero elapsed time.
- 8.1.3 Remove the testpiece from the water bath, dry it and mount in the tensile creep apparatus which is at the temperature at which the measurements are to be made. It is advisable to turn environmental chambers off when carrying out this operation. This avoids a period of slight overheating which can occur after the chamber door is closed if they are not switched off during the period when the sample is mounted.
- 8.1.4 Loads should be applied at the following times after quenching and creep data collected for the periods given (which are kept at $\sim 0.3t_e$).
- 3 hours: measurement period 50 minutes
 - 7 hours: measurement period 2 hours
 - 24 hours: measurement period 7 hours
 - 72 hours: measurement period 21 hours
 - 240 hours: measurement period 72 hours.

These times have been selected to allow for recovery of the testpiece between successive tests. Information regarding the selection of an appropriate load is given in Section 5.3.1.

- 8.1.5 It is important to zero the transducers before the start of each test. This is because as the material ages it decreases in length giving rise to an apparent strain in the absence of a load.

Note

It is recommended that the testpiece should remain mounted within the test machine during the 2 weeks required to complete this test programme. This avoids the possibility of introducing alignment errors due to the removal and remounting of the testpiece.

8.2 Analysis of creep data

- 8.2.1 Using a least-squares optimization algorithm determine optimal values for D_0 , t_0 and for m for each set of short-term data according to the equation

$$D(t) = D_0 \cdot \exp\left(\frac{t}{t_0}\right)^m \quad (7)$$

Typical starting estimates for these parameters which would apply to a range of materials would be $D_0 = 0.5 \text{ GPa}^{-1}$, $t_0 = 1 \times 10^6 \text{ s}$ and $m = 0.3$.

- 8.2.2 Plot D_0 , $\log t_0$ and m against $\log t_e$ (s). Look for any dependence of D_0 or m on elapsed time. Whilst m is normally found to be constant for a given set of conditions, D_0 tends to decrease slightly with increasing elapsed time. Note that for some materials D_0 can be taken as a constant if it has a negligible dependence on elapsed time. There are materials where there is some evidence that m depends on elapsed time e.g. certain grades of polypropylene however this dependence has yet to be clearly established and for the present will be excluded from the Code.
- 8.2.3 *Case 1:* Assuming that both D_0 and m are independent of elapsed time, take average values for these parameters and refit equation (7) to the data in order to calculate appropriate values of t_0 .
- 8.2.4 *Case 2:* If D_0 does depend on elapsed time then the following relationship applies

$$D_0 = W \times t_e^{-v} \quad (8)$$

Plot $\log D_0$ against $\log t_e$ and determine the intercept $W(\text{GPa}^{-1})$ and slope v .

Recalculate values of t_0 using a constant value for m and calculated D_0 values based on equation (8).

- 8.2.5 Plot $\log t_0$ against $\log t_e$. This plot is linear with a slope of μ and an intercept of A according to the relationship

$$t_0 = A \times t_e^\mu \quad (9)$$

Determine values of $A(\text{s})$ and μ .

Chapter 9: Procedure B

- Experimental programme
- Analysis of creep data

9. Procedure B: Determination of long-term creep parameters at low stresses

To fully characterise the creep behaviour of plastics as a function of age and creep time it is necessary to derive two further parameters, C and μ' in addition to those derived from short-term measurements. These can only be obtained from long-term tests which typically run for a limited period of three weeks.

9.1 Experimental programme

9.1.1 The procedure for obtaining long-term data initially follows that described in Sections 8.1.1-8.1.4. Loads should be applied at the following times after de-ageing the testpiece:

- 7 hours
- 24 hours
- 72 hours

The recommended period for collecting data is 2×10^6 s (~ 3 weeks) for all elapsed times. This corresponds to t/t_e ratios of 79, 23 and 7.7 respectively. Whilst the duration of the tests could be reduced for the shorter elapsed times it is often these data which are the most sensitive to the parameters used in the long-term creep function and hence the most useful as long as these parameters do not change with elapsed time. In practice long-term tests can be conducted in parallel using a number of test rigs. This reduces the period of time required to obtain a complete set of data.

9.2 Analysis of creep data

9.2.1 Follow the procedures given in Section 7 to obtain plots of $D(t)$ against t for each elapsed time as shown in Figure 3.

9.2.2 The long-term creep function

$$D(t) = D_0 \exp \left[\int_0^t \frac{du}{(A^2 t_e^{2\mu} + C^2 u^{2\mu'})^{0.5}} \right] \quad (10)$$

contains two unknowns, C and μ' . These are determined using a least-squares optimization algorithm using the values of A and μ derived from the short-term data as starting values.

Chapter 10: Procedure C

- Experimental programme
- Analysis of creep data

10. Procedure C: Determination of creep parameters at different temperatures

Whilst the parameters obtained by following procedures A and B enable predictions of creep to be made as a function of sample age and creep time, they are only valid at the temperatures at which data are available. This procedure describes a method for deriving the temperature dependence of these parameters which enables predictions of creep behaviour to be made at temperatures at which there is no supporting data. Due to the complexity of temperature effects we recommend that only interpolations be made to predict creep curves.

10.1 Experimental programme

- 10.1.1 Repeat procedures A and B described in Sections 7 and 8 at 3-4 different temperatures separated by intervals of approximately 10 °C.

Care must be taken in planning a series of creep tests at elevated temperatures in order to avoid the complexity of viscous flow and practical problems associated with measuring strain. At high temperatures it is likely that the testpiece will show signs of yielding in long-term tests as shown in Figure 7. The analysis of such data is currently beyond the scope of this document. However, steps can be taken to avoid yielding by lowering either the test temperature or the applied load, noting that choosing the latter option can result in tests having to be repeated at lower temperatures to ensure comparability. It should also be recognised that non-linear behaviour of the material may be observed at higher temperatures at stresses which give rise to linear behaviour at lower temperatures. This topic is discussed in Section 5.3.1.

The type of transducer employed has an influence on the temperature range over which creep data can be obtained, for example, it may not be possible to electrically zero the voltage output from strain gauges at all test temperatures due to thermal expansion or contraction of the testpiece. The use of LVDT's with knife edge contacts can pose problems at high temperature both due to softening of the polymer and in mounting the transducers on to the specimen at the test temperature which, as it is done by hand becomes difficult at temperatures in excess of about 65°C! If it is necessary to obtain creep data at temperatures in excess of this limit then an alternative approach to measuring the sample extension should be sought.

10.2 Analysis of creep data

- 10.2.1 The analysis of both the short- and long-term creep data at each temperature follows the procedures described in Sections 8.2 and 9.2. At the higher test temperatures, the material may begin to yield which will sometimes be obvious on completion of the test as the testpiece will show signs of necking. In other measurements the testpiece will not show any visible signs of necking but evidence of viscous flow will be apparent in plots of $D(t)$ versus $\log t$ as shown in Figure 7. The analysis of this flow process is beyond the scope of this guide.
- 10.2.2 Plot $\log t_0$ against $\log t_e$, for all data at all temperatures. Check to see if μ has any temperature dependence. This guide does not cater for a situation where μ is temperature dependent, thus the user has a choice of either developing an appropriate function to describe its dependence or to assume that it is constant.
- 10.2.3 Assuming μ to be independent of temperature, plot $\log A$ against $1/T$ (K). For amorphous polymers this plot will be linear at temperatures well below that of T_g as shown in Figure 8. Fit a function of the form $\log A(T) = F/T + H$ over the linear range of the plot.
- 10.2.4 Plot W against temperature (in °C). Fit a quadratic function to the data of the form $W(T) = a_0 + a_1T + a_2T^2$.
- 10.2.5 The function for describing short-term creep at different temperatures is now

$$D(T, t) = W(T)t_e^{-\nu} \exp\left(\frac{t}{(A(T)t_e^\mu)^m}\right) \quad (11)$$

where the temperature dependences of W and A are known.

- 10.2.6 Plot $\log C$ against $1/T$ (K). Fit a function of the form $\log C(T) = J/T + L$ to this plot as shown in Figure 8.
- 10.2.7 The function for describing long-term is now

$$D(t) = W(T)t_e^{-\nu} \exp\left[\int_0^t \frac{du}{(A^2(T)t_e^{2\mu} + C^2(T)u^{2\mu})^{0.5}}\right] \quad (12)$$

where the temperature dependences of A , W and C are known.

- 10.2.8 If any of the above functions are unsuitable for describing the temperature dependence of A , C and W then the user either has the opportunity to derive more appropriate functions or abandon any attempts to model the relationship between these parameters and temperature. If the latter option is followed then equations (11) and (12) can only be used to predict the creep behaviour of the material at the temperatures at which measurements are available.

Chapter 11: References and figures

- References
- Further reading
- Figures

11. Reference, further reading and figures

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11.2 Figures

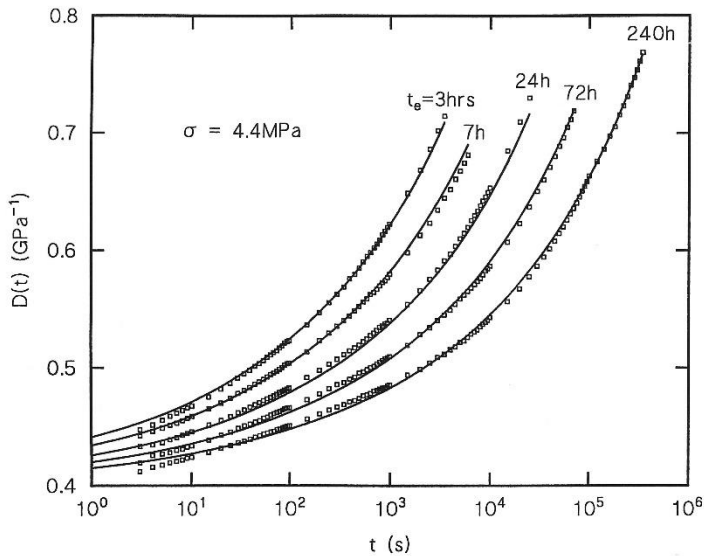


Figure 1 Short-term creep data obtained from an epoxy resin (Evide TE251) as a function of elapsed time, t_e . The solid lines correspond to fits of equation (1) with m constant. Values of t_0 and D_0 were re-calculated using equations (2) and (3).

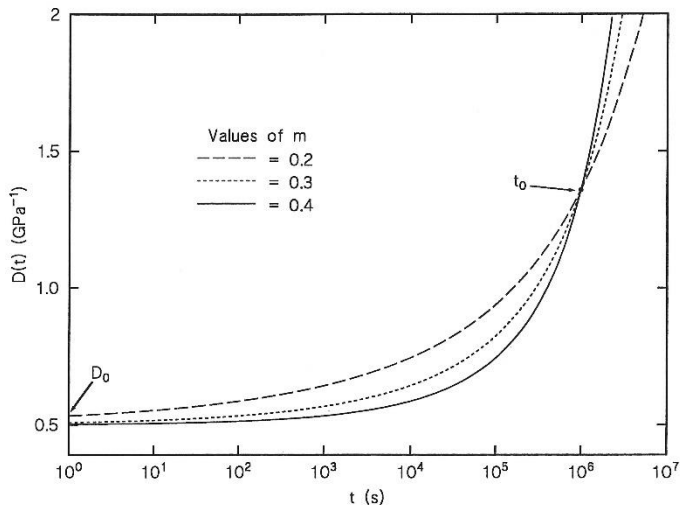


Figure 2 Plots of equation (1) where $D_0 = 0.5$ and $t_0 = 1 \times 10^6$ s which illustrates the influence of changes in m on the shape of the curve.

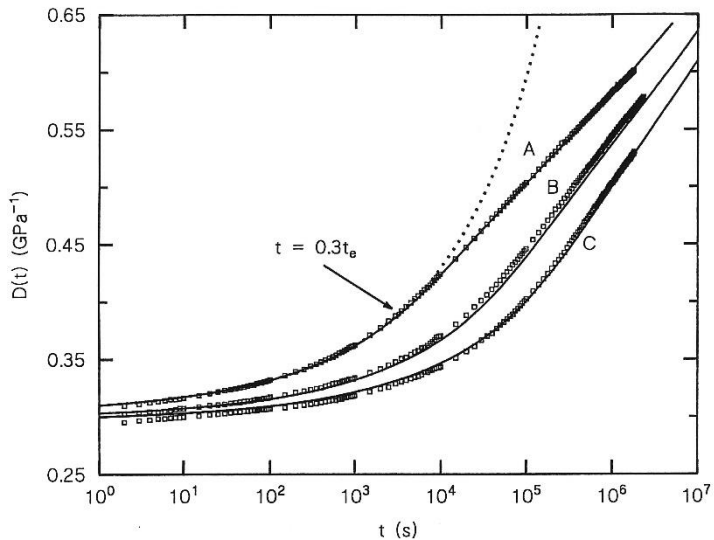


Figure 3 Long-term creep of PVC as a function of elapsed time. The solid lines are calculated fits to the data based on equations (2), (3) and (4). The dashed line is the predicted creep behaviour of a 3 hour old testpiece in the absence of further ageing as given by equation (1).



Figure 4 NPL over-slung tensile testing machine for measuring the creep of plastics.

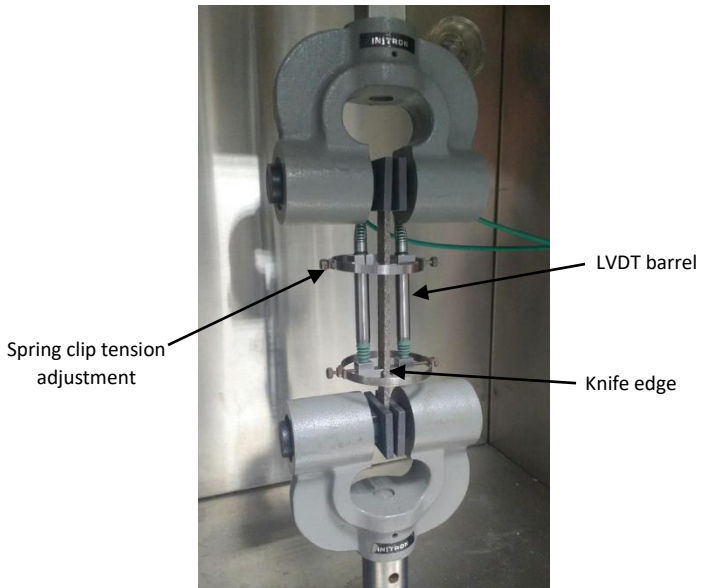


Figure 5 A tensile extensometer composed of two knife edges mounted on an LVDT. The spring clips are used to clamp the extensometers to the testpiece.

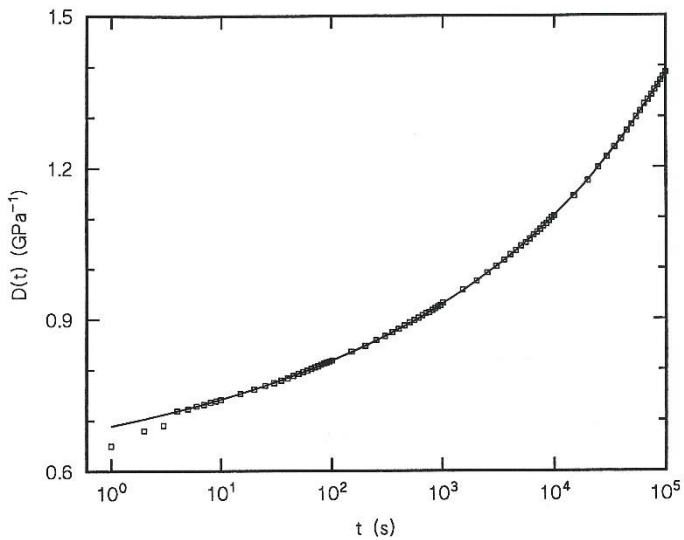


Figure 6 An illustration of how 'slow' application of a load to a testpiece can result in data which is inconsistent with the subsequent creep data and cannot be described by equation (1). Attempts to fit the entire data set using a least-squares algorithm will result in a poor fit.

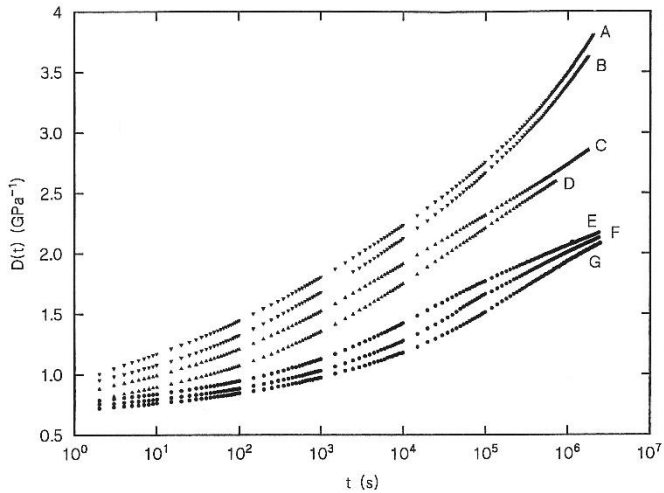


Figure 7 Long-term creep data for polypropylene as a function of stress and elapsed time at 23 °C. The data obtained at a stress of 3 MPa at elapsed times of 7, 24 and 72 hours (curves E, F and G) show a progressive reduction in the creep rate at long times. This feature is less pronounced in data obtained at 9 MPa for elapsed times of 7 and 24 hours (curves C and D) whilst data obtained at 12 MPa for the same initial elapsed times (curves A and B) shows an increased creep rate at long times. This is due to the occurrence of viscous flow at the higher stresses. This process will also be observed at high temperatures for low stresses e.g. 3 MPa at 60 °C.

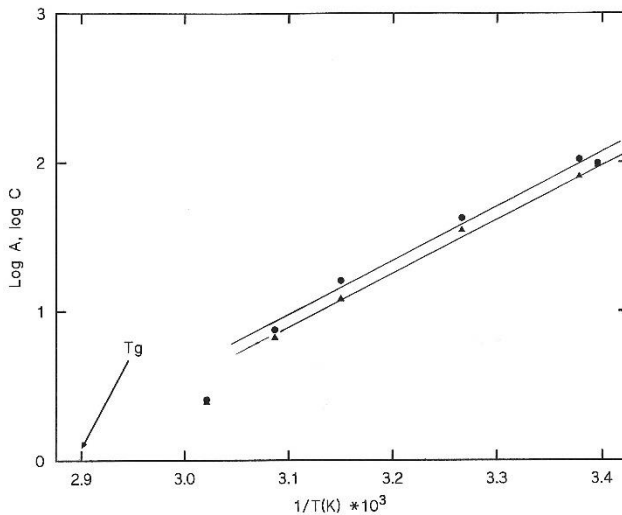


Figure 8 Plots of log A and log C against inverse temperature for PVC ($\sigma = 5$ MPa). Note that both log A and log C deviate from linearity at temperatures approaching the T_g of the material (~ 70 °C).